THE UNIVERSITY OF ALBERTA

"THE EFFECTS OF CONCRETE COMPRESSIVE STRENGTH
ON TRANSFER BOND OF PRESTRESSED MEMBERS"

A THESIS
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ABSTRACT

A program designed to investigate the effects of concrete compressive strength on transfer bond length consisted of testing thirty concrete specimens, each prestressed with one 3/8-inch diameter strand positioned at the longitudinal centroid. The change in strain was determined from readings taken at two-inch intervals on the surface of the concrete before and after strand release. These strain readings indicated the rate of bond transfer and the point at which this transfer was complete. The strands were released at concrete compressive strengths of approximately 3,000 p.s.i., 4,000 p.s.i. and 5,000 p.s.i.

The test results indicated that the transfer bond length increased with decrease in compressive strength of the concrete.

Records were kept of the maturity (the product of the temperature of the concrete in degrees Fahrenheit and the time cured in hours) of each specimen. Results showed that heated concrete gains strength in relation to its maturity approximately in accordance with the same law as holds for normally cured concrete.

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NOTATION

The following notation is used in the following pages:

f_c - concrete compressive strength as indicated by the ultimate compressive strength of a standard 6" x 12" test cylinder tested in a compression type testing machine with a capacity of 300,000 lbs. The rate of loading was approximately 3,000 p.s.i. per minute.

E_s -concrete secant modulus of elasticity (slope of the line from the origin to the value at a stress of 1062 p.s.i. on the load versus strain plot).

D.H. -degree hours (units of concrete maturity).

E_c -concrete chord modulus of elasticity (slope of the chord on load versus strain plot between stresses of 354 p.s.i. and 1,062 p.s.i.).

CHAPTER 1: INTRODUCTION

1-1 Nature of Bond

The transfer length and rate of prestress build-up in pretensioned prestressed concrete members may be of considerable importance since in short members the working bending moments, and in some thin sections the shear resistance, may depend upon this transfer length. It is important, too, when pretensioned units are joined to form continuous structures.

Bond in pretensioned concrete beams is of two types, namely, transfer bond and flexural bond. Transfer bond utilizes a part of the available tensile strength of the strand to establish compression in the concrete. Flexural bond results from the action of external loads on beams. After cracking the increase in the strand stress above effective prestress develops flexural bond stress between the strand and the concrete.

Prestress transfer bond exists near beam ends after the load in the tensioned strand has been transferred to the concrete member. The length over which this transfer is made is termed the prestress transfer length and depends mainly on the amount of prestress, surface condition of the strand, the strength of the concrete, and the method of strand stress release. Three factors which contribute to bond performance are adhesion between concrete and steel, friction between concrete and steel and mechanical resistance between concrete and steel. In the transfer zone, reduction in the tensile

strain in the strand does not equal the compressive strain in the concrete at the same point. There is relative movement of steel and concrete, and accordingly adhesion cannot contribute to prestress transfer. Friction is considered to be the principal factor causing stress transfer from pretensioning steel to the concrete. As the tension in the strand is released, the strand diameter tends to increase, thus producing high radial pressure against the concrete, which in turn produces high frictional resistance in the transfer zone. Mechanical resistance probably contributes little to prestress transfer in the case of individual smooth wires, but it may be a factor of some significance in the case of strand.

1-2 Maturity

In view of economic requirements, many prestressed concrete fabricators operate their plants on a 24-hour cycle. With approximately six hours required to strip, clean and reassemble the forms, and to pretension the reinforcement, the total time lapse between casting and prestress release will be about 18 hours. This 18-hour period includes the pre-heat period, the temperature rise period, and the maximum temperature period during which the curing temperature remains constant. The optimum manufacturing program requires a knowledge of the effects of high temperatures on the strength progress of the concrete.

Maturity is the product of the temperature of the concrete in degrees Fahrenheit and the number of hours the

concrete is cured at this temperature, and is a measure of the strength of concrete at any instant while it is being cured.

In a concrete mixture, the portland cement and the water forms a paste or glue which gradually hardens to cement the aggregate particles together. This hardening of the paste is caused by a chemical reaction between the cement and the water. It has been shown that if the temperature gradient of the concrete, after the time of mixing, does not exceed 35 degrees F. per hour, heated concrete gains strength in relation to its maturity approximately in accordance with the same law as holds for normally cured concrete. Concrete which is raised in temperature more rapidly than 35 degrees F. per hour, or is permitted to dry out, or is heated above 165 degrees F. does not obey this law, and is affected in strength at a later age.

1-3 Experimental Investigations of Transfer Bond

A search of literature did not yield any references which deal directly with the effects of early strand release on the transfer bond stresses of members prestressed with 3/8 in. diameter strand. The following are some references pertinent to this investigation.

Base[1] developed a simple and quick method for measuring the change in strain on the surface of the concrete when the stress is transferred from the steel to the concrete. The investigation consisted of tests on 140 members produced in five widely separated factories in England and Scotland,

and more than 100 members produced in two laboratories.

The size of the factory members varied from small lintels to 12in. x 4in. beams, and 45in. x 13in. slabs. The prestress varied from 800 p.s.i. to 2,500 p.s.i. Plain wires of 0.08in. diameter were used. The concrete strength was not reported. Sixty-eight of the laboratory specimens were 4in. x 6in. cross section, 12ft. long, and uniformly stressed to 2,000 p.s.i. by ten wires. Plain, indented, and crimped wires 0.2in. in diameter were used. Concrete cube strength varied from 4,850 p.s.i. to 7,410 p.s.i. Ten laboratory specimens 6in. x 2in. cross section, 35in. long and prestressed by two wires were tested. The wires were 0.2in. in diameter, plain or crimped. Concrete cube strength varied from 4,000 p.s.i. to 10,000 p.s.i.

Strain was measured with a Demec strain gage, with 8in. gage lengths formed by 0.04in. diameter holes drilled in pairs of 1/4in. diameter, 1/16in. thick, stainless steel discs, fixed to the surface of the member. Gage lengths were pre-formed in the laboratory by gluing the discs into holes punched at 8in. centres in long 3/4in. wide strips of thin cardboard. The backs of the discs were coated with sealing wax so that the factory work was limited to fixing the cardboard strips to the unit with adhesive tape and melting the sealing wax by application of an electric soldering iron to the faces of the steel discs. Gage lengths were usually overlapped seven inches and the centre of the first gage length was usually five inches from the end of the member. Readings were taken

on the gage lengths immediately before and after release of the stressing wires and the strains were then calculated. Curves were plotted through the series of points obtained at one-inch centres and this gave an indication of the build-up of stress in the concrete. Factory results indicated no significant difference in the average results, or in the scatter, obtained in the five different factories.

A comparatively small number of results were obtained on 0.08in. diameter high-tensile steel wire, but they appeared sufficient for a reasonable assessment. Full transmission occurred at between 6in. and 13in. with a build-up of 80% at between 4in. and 9in. The build-up 6in. from the end of the unit was between 30% and 100%. A number of cases of honeycombing at the ends of units, resulting in greatly increased transmission lengths, were noted.

Several units with o.2in. diameter high-tensile steel wire were tested. The wire was plain, indented or crimped, and varied from clean to "well rusted". No significant difference was found between plain and indented wire, nor was there any noticeable effect due to rusting of the wires before use. Seventy percent of the transmission lengths were 20in. or less and the average value was between 18in. and 19in. The transmission length of the indented wire was between 10in. and 27in. About 70% were 20in. or less and the average was about 19in. The results with crimped wire were significantly better than for plain wire and indented wire; the transmission length was between 10in. and 18in. with an average of 13in.

A number of results were obtained on units in which the o.2in. wires were released by flame-cutting; a process which resulted in transmission lengths of many feet. In some units which were designed for a uniform prestress, flame-cutting of the wires resulted in tensile cracks in the top half of the section four feet from the ends of the units. A small number of results obtained in a factory using 0.276in. diameter plain wire showed a scatter from 12in. to 45in. for full transmission.

Laboratory results on 68 units with 0.2in. diameter wire showed that about 90% of the transmission lengths were below 15in. and about 70% were 12in. or less. Results were slightly poorer with plain wire than with indented wire, but concrete cube strength was less with plain wire than with indented wire; this was probably the primary cause of the variation in transmission length.

Tests of ten units in the laboratory; five with plain wire and five with wire with a large crimp; indicated shorter transmission lengths for the wire with a large crimp when concrete cube strength was low and conditions were poor, but plain and crimped wire gave similar short transmission lengths when the cube strengths were high and conditions were good.

A few tests with 0.276in. diameter wire indicated an average transmission length of 18in. Tests on six beams stressed with 5/16in. diameter, 6 x 1 strands, gave twelve transmission lengths in the range of 9in. to 19in. This was

similar to the transmission length expected for 0.2in. plain wire although the strand carried over twice the load.

A 3/4in. diameter strand with a working load of 25 tons, had transmission lengths of 12in. and 17in. at the two ends of a 5in. x 10in. specimen. The bursting stresses, however, produced cracks extending about a foot along the beam at each end, despite spiral reinforcement around the cable. The concrete cube strength at transfer was 4,875 p.s.i.

Janney[(2)] studied transfer bond stresses in prestressed concrete prisms of small cross section. Variables incorporated into this investigation were: four wire diameters and one strand diameter, two concrete strengths, and three surface characteristics of wire and strand. The total number of specimens tested was not reported.

The specimens were 2in. x 2in. cross section and 72in. or 96in. long. A number of wire diameters and surface conditions were used and all reinforcing was prestressed to 120,000 p.s.i..

Stress in the wire was measured by electric resistance strain gages, one on the outside of the specimen at each end and one at the midpoint of the prism. Stress in the strand was measured by four electric resistance strain gages, two at each end on the outside of the specimen and one at the midpoint of the prism. Twenty-six electric resistance strain gages were placed along the sides of each prism after moist curing was completed. Immediately before the pre-tension was released, readings were taken on all gages on the surface of the

concrete and on the steel. The tension was released from the steel to the concrete and again complete strain readings were taken. The data established the pre-tension in the steel just prior to release, the tension retained in the steel at the centre of the specimen after release, and the distribution of prestress.

The length of embedment necessary to transmit the steel stress to the concrete prisms, varied from approximately 18in. to 23in. with the increase in wire diameter from 0.100in. to 0.276in. respectively. Prisms prestressed with 0.162in. diameter clean wire, and the wires released at concrete strengths of 4,500 p.s.i. and 6,500 p.s.i., indicated transfer bond transmission lengths of 21in. and 23in. respectively. Prisms prestressed with 0.162in. diameter rusted wire had a transfer bond transmission length of 11in. and similar prisms prestressed with clean wire had a transmission length of 21in. A comparison of clean wire and lubricated wire is as follows: (a) 0.100in. diameter clean wire - transmission length 16in., (b) 0.100in. diameter lubricated wire, transmission length of 27in., (c) 0.276in. diameter clean wire - transmission length of 20in., (d) 0.276in. diameter lubricated wire, transmission length of 30in.

Hanson and Kaar[3] investigated the effect of embedment length and diameter of strand on the bond performance of prestressed beams. The influence of reduction in concrete strength was investigated to a limited extent. Their test program involved 47 beam tests divided into four series.

The test beams were instrumented to record the continuous development of flexural strains and the subsequent evidence of bond slip. Electric resistance strain gages were cemented along the helical individual wires of the twisted strand. Dial indicators reading to 0.001 in. were used to measure beam deflections. Dial gages were also mounted at both ends of each beam to detect slip of the projecting strand ends relative to the concrete.

All beams were tested to failure in a hydraulic testing machine. Beams of two series were loaded at midspan through either a ball or roller arrangement. All other beams were loaded at two points through rollers spaced twice the beam width on either side of midspan. The beams were supported on concrete piers with a free roller at one end and a pivot at the other. The strand tension was released at a concrete strength of 4,500 p.s.i. except for the lower strength specimens of one series, which were released at a strength of 3,500 p.s.i. The individual beam tests were generally conducted in about 30 minutes, with a continuously increasing load.

The results of the tests on 47 beams support the flexural bond wave theory proposed by Janney[2] and confirm that general bond slip occurs in a pretensioned beam when the peak of the flexural bond stress wave reaches the stress transfer zone. It was found that strand size and embedment length have a considerable influence on the value of the average bond stresses at which general bond slip occurs.

From the test results, curves were drawn to indicate the bond stress at which slip would probably occur for particular strand sizes and embedment lengths. From these curves design criteria for the avoidance of general bond slip were obtained. For the strand used in this investigation, the minimum embedment lengths were approximately as follows: 70in. for 1/4in. diameter strand; 106in. for 3/8in. diameter strand; and 134in. for 1/2in. diameter strand.

Rusting the strand raised the moment at general bond slip, and the ultimate moment of resistance, relative to identical beams with clean smooth strand. The seven wire strand developed additional beam strength, due to mechanical bond resistance, even after general bond slip in the end had occurred.

Nordby and Venuti[4] tested 27 beams cast from conventional and expanded shale aggregate concrete and prestressed with steel strand. The project was undertaken with a two-fold purpose: (1) to study the use of a lightweight aggregate in bonded-type prestressed concrete beams; and (2) to explore the effects of fatigue loading on prestressed concrete beams made with both conventional stone aggregates and expanded shale aggregates. Some knowledge was also gained on bond between steel strand and the two concretes as a by-product of the other tests. Only the portion of the report related to bond is summarized as follows: Two cross sections of beams were used; $4\frac{1}{2}$in. x 6in., and 10in. x 5in. All beams were 12 feet long. Beams were pretensioned with seven-wire

uncoated stress-relieved strands of 5/16in. and 3/8in. diameter. Tests on 3/8in. diameter strands indicated an ultimate strength of 272,000 p.s.i.; modulus of elasticity of 28.75 x 10^5 p.s.i and stress at 0.2% permanent strain of 240,000 p.s.i. Concrete compressive strength at strand release varied from 4,000 p.s.i. to 5,000 p.s.i.; and the 28-day strength varied from 5,500 p.s.i. to 6,500 p.s.i.

Static loading of the beams was accomplished in a large hydraulic testing machine. Deflections were measured at centre-line and dial gages were attached to the ends of the beams to record the slip of the strand. Electric resistance strain gages were attached both externally on the concrete surface and internally on the surface of the steel strand for strain measurement.

It was found that slip occurred below bond stress intensities computed by conventional equations. It did not appear that designing with a bond stress limitation would insure against failure; consequently no limiting bond stresses were recommended. It appeared rather that an embedment length between the end of the beam and possible crack positions should be specified, coupled with an allowable stress increase in the prestressing strand and in the ultimate concrete strength. Based on the extrapolation of the data for the 5/16in. and 3/8in. diameter strands, it appeared that an anchorage length limitation of a rather severe nature may be required to develop the ultimate strengths for strands greater than 3/8in. diameter.

Keuning[5] investigated anchorage zone stresses in pretensioned beams. The specific goal of the study was to determine a bond versus slip relationship for 1/4in. diameter strand.

The series comprised tests with embedment lengths of 1.5, 3, 6 and 9 inches. Each test represented two specimens; one contained an unstressed strand and the other a prestressed strand. The basic specimen cross section was 4in. x 4in. and concrete strengths were 5,000 p.s.i.

The special testing frame used for the tests was similar to the frame shown in Figure 4. Two aluminum dynamometers were used to measure the load in the prestressed specimens. For the unstressed specimens, only one dynamometer was used. The slip of the concrete with respect to the strand was measured with the use of travelling microscopes; one placed at the loaded end and the other at the unloaded end. The slip was measured by determining the relative movement of scribe marks on 0.015 gage metal sheets; one sheet bonded to the concrete and the other to the strand.

The most significant characteristic of the load-slip curves reported was their nearly elasto-plastic shape. In general, in the load-slip curves for plain wires or bars, a maximum load was reached at a small slip, after which the bond resistance decreased to a small fraction of the maximum. On the other hand, the load-slip curves for bars with adequate deformations increased continuously with slip until the surrounding concrete was destroyed. The load-slip

curves for the 1/4in. strand represented an intermediate case between the two types of response. A maximum was reached after which the resistance decreased as further slip occurred. However, the bond resistance reached a stable condition, and no further reduction was observed at loaded end slips as high as 0.3in. Furthermore, the resistance corresponding to the stable condition was 85% of the maximum load. This condition suggested that there was little difference between the average nominal bond stresses obtained from specimens having various lengths. There was no definite trend in the bond stresses with embedment length. As would be expected, the pretensioned strands resulted in higher bond stresses than for those which were not pretensioned. However, the difference was small. The test results indicated that the transfer length for the 1/4in. diameter strand tested would be less than 10in. for the working load and 20in. would be adequate to develop its strength under short-time loading conditions.

1-4 Experimental Investigations of Maturity

A search of literature did not yield any information pertaining directly to maturity of concrete cured in air, but the following are investigations of maturity versus compressive strength of steam cured concrete. Saul[(6)] summarizes the conclusions drawn from experimental work designed to find the optimum concrete curing procedures. The specimens were 4in. concrete cubes. The curing chamber, 6ft. 3in. long, consisted of two 36in. concrete pipes laid horizontally end to end and surrounded with clinker aggregate concrete.

It had relatively steam-tight doors at both ends, and was divided by a metal partition into two unequal compartments. The smaller of these housed a vessel to hold 16 gallons of water, equipped with an electric immersion heater which could be adjusted to produce any required out-put of steam. The steam was admitted to the top of the longer compartment and guided down the sides by a metal baffle plate, which prevented condensation on the specimens. Four remote-reading thermometers were provided, which could be placed in different positions in the chamber. A remote-reading thermocouple was also provided to record the actual temperature of the specimens.

It was concluded that the most important factor in steam curing at atmospheric pressure is the rate of initial temperature rise reckoned from the time of mixing. Relatively good results were obtained if the temperature of the concrete did not reach 50 degrees Centigrade until 2 hours, nor 100 degrees C. until 6 hours after the concrete was mixed.

Menzel(7) obtained his data from three papers; Shideler(8) , Saul(6), and Chamberlin(9). From the test data it was concluded that good results were obtained with steam curing at atmospheric pressure when: (1) steaming was delayed for two or three hours after moulding; (2) the temperature rise in the concrete was limited to about 35 degrees F. per hour; (3) the maximum temperature in the concrete ranged between 130 degrees F. and 165 degrees F. during the constant temperature of the cycle; and (4) the steaming

period was followed by moist curing at normal temperature (70 degrees F.) until 7-day age and then stored in air until 28-day age. With exposure to steam for 18 hours at 130 degrees F., or for 24 hours at 165 degrees F., the preceding four-point curing procedure provided nearly the same strength at 28-day age as was obtained with a basic curing of 7-day fog curing at normal temperatures and 21-day storage in air. Hence from the standpoint of 28-day strength, there was no advantage in steam curing at 165 degrees F. instead of 130 degrees F. However, concrete cured at 165 degrees F. produced a higher early strength than concrete cured at 130 degrees F. since a 2-day strength was attained in 16 hours at 165 degrees F. compared with 21 hours at 130 degrees F. Without the added moist curing until 7-day age, the strength at 28-day age was 80% of the strength of the concrete which received additional moist curing after steaming.

Hanson[(8)] investigated the effect of various steam curing procedures on the compressive strength, indirect tensile strength, and elastic properties of concrete, with particular emphasis on steaming procedures compatible with the time requirements of modern prestressing plants. In these plants the usual time lapse from casting to steam shut-off remains nearly constant at 18 hours. In Hanson's investigation the delay period was varied prior to steaming, then the temperature was raised at 20 degrees F. to 80 degrees F. per hour up to three values of maximum temperature; 125 degrees F., 150 degrees F., and 175 degrees F.

Standard 6in. x 12in. test cylinders were used as specimens. The mixes were proportioned to obtain 6,000 p.s.i. compressive strength after moist curing at 70 degrees F. for 28 days. The laboratory heating plant boilers supplied live steam to the steam room. Temperatures were controlled manually during the temperature rise period, but an electrical thermostat assumed control at the constant temperature level. Steam room temperatures were measured by thermocouples located at the level of the concrete at stations near the rear, middle and front of the room. Additional thermocouples were inserted in typical concrete specimens for measurement of concrete temperatures. All thermocouples were monitored with an automatic recorder.

Those cylinders that were tested for compressive strength also provided the data for static modulus of elasticity. Modulus of elasticity was determined from axial strain measurements obtained by a dial gage mounted on a frame secured to the concrete specimen. After pre-loading, strain readings were taken at 100 p.s.i. and 1,200 p.s.i. and the modulus was computed from the stress and strain increments. The tensile strength was determined by the "Brazilian" or cylinder-splitting method.

The following conclusions were derived from the data of this investigation: (1) The effects of variable steam curing procedures on modulus of elasticity and tensile-splitting strengths are similar to those on compressive strength, but of a lesser degree. (2) Under the steam

curing conditions employed in this investigation, the optimum steaming conditions appear to incorporate a pre-steaming period of approximately five hours with a rate of temperature rise of 40 degrees F. per hour. There appears to be only moderate advantage in obtaining maximum sustained temperatures above 150 degrees F. (3) Deviations from these optimum curing conditions of less than plus or minus two hours of temperature rise rate will result in only minor changes in concrete characteristics. (4) Application of steam to the concrete as soon as one hour after casting, may be quite detrimental to the compressive strength. If particular plant procedures require this early application of steam, it appears that the rate of temperature rise should be restricted to less than 20 deg.F. per hr.

1-5 Summary

The consensus of the papers was that transfer bond strength increased with concrete compressive strength. However, this increase was insignificant compared to the effects of other variables on transfer bond strength.

All authors concluded that concrete, when steam-cured at higher temperatures, gains strength in relation to its maturity approximately in accordance with the same law as holds for normally cured concrete, if recommended curing procedures are observed.

CHAPTER 2: SCOPE OF INVESTIGATION

2-1 Object of Investigation

The primary purpose of this investigation was to establish the effects of concrete compressive strength on the transfer bond length in members prestressed with 3/8 inch diameter strand. Thirty concrete specimens were tested with concrete strengths varying from 3,000 p.s.i. to 5,000 p.s.i. Each specimen was prestressed with one 3/8 inch diameter strand initially stressed to 14,000 pounds. In the course of the investigation, a study was made of maturity (the product of the concrete temperature in degrees Fahrenheit and the time cured in hours) as a method of predicting strength of concrete.

CHAPTER 3: TEST SPECIMENS

3-1 Prisms

Thirty specimens were tested in ten groups of three. The specimens were 3-3/4 inches x 3-3/4 inches in cross section, 40 inches long, and prestressed with one 3/8-inch diameter strand at the longitudinal centroid. The cross section was calculated to produce approximately 1,000 p.s.i. initial prestress in the concrete. A specimen mounted in the test frame is shown in Figure 1. All prisms were cast from identically proportioned mixes. In three groups the bond was broken over a portion of the length by placing a 3/8-inch diameter flexible plastic hose over the strand before the concrete was poured. Six standard test cylinders, 6 inches x 12 inches, were cast with each group of three prisms. Details of specimens are as follows:

Series	Number of Specimens	Concrete Strength (p.s.i.)	Slump (in.)	Strand Prestress (lbs.)
1	3	3,065	3.00	14,000
2	3	5,065	3.00	14,000
3	3	4,407	3.00	14,000
4	3	3,097	2.75	14,000
5*	3	4,412	4.75	14,000
8	3	3,030	3.00	14,000
9	3	5,120	3.00	14,000
10	3	4,248	3.00	14,000

*coarse aggregate was omitted from mix

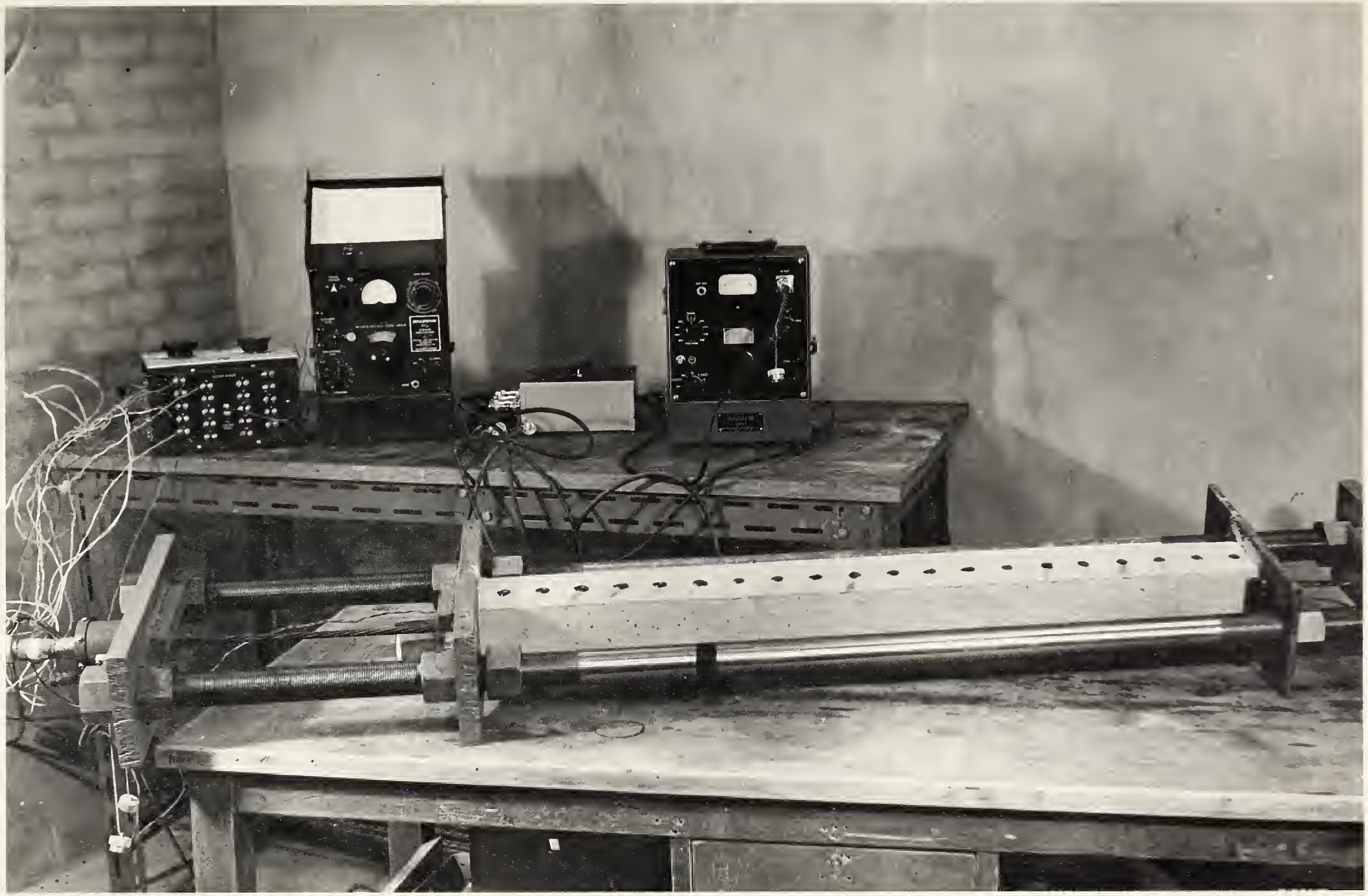

FIGURE 1 - TESTING FRAME WITH PRISM IN POSITION

CHAPTER 4: MATERIALS, MIX AND MIXING

4-1 Materials

The washed rock was blended from 1 inch maximum to #4 minumum. The results of a sieve analysis are tabulated in Table 1. Results of a sieve analysis of the sand are also tabulated in Table 1. The type (3) high early Portland cement used was from one batch. Water was obtained directly from the City of Edmonton water mains.

The 3/8in. diameter prestressing strand was manufactured by the American Steel and Wire Division of the United States Steel Corporation. The strand conformed to A.S.T.M. specification A-421-58T. Stress-strain plots for two strand specimens are shown in Figures 2 and 3. The modulus of elasticity obtained from Figure 1 was 23.28×10^{6} p.s.i. and from Figure 2 was 23.22×10^{6} p.s.i. The average proportional limit stress of the two specimens was 187,500 p.s.i.

4-2 Mix Proportions

The mix proportions were based on suggested mixes for concrete of medium consistency[9]. These mixes are governed by the maximum size of the coarse aggregate and the fineness modulus of the fine aggregate. The strength is controlled by the water-cement ratio.

Three-inch slump was chosen to simulate average conditions of plant manufacture. The water-cement ratio was chosen to yield a compressive strength of 3,500 p.s.i. at 2,175 D.H. maturity. The value of 2,175 D.H. was found to be the ap-

TABLE 1

SIEVE ANALYSES OF AGGREGATES

Coarse Aggregate	
Sieve Size	Percent Retained
1"	0.00
3/4"	20.32
3/8"	53.60
#4	25.85
pan	0.23
Colour Test No. 1	

Fine Aggregate		
Sieve Size	Percent Retained	Accumulated % Retained
4	1.6	1.6
8	12.9	14.5
16	14.0	28.5
30	11.9	40.4
50	45.0	85.4
100	12.5	97.9
200		100.0
pan	2.1	
Colour Test No. 2		
Fineness Modulus - 2.68		

proximate value of maturity obtained in local plants at strand release. This mix design was used throughout the investigation. The proportions for a 3 cu.ft. mix are as follows: 77.2 lbs. of Type (3) cement, 39.5 lbs. of water, 133 lbs. of fines, and 196 lbs. of coarse aggregate.

4-3 Mixing Technique

All concrete was mixed three minutes in a tilting drum-type mixer of 3 cu.ft. capacity. The slump was determined immediately after mixing. Each pour, consisting of three specimens and six cylinders, required one batch of concrete.

4-4 Placing Techniques

Test specimens were poured in one lift and vibrated with a high-frequency internal vibrator. Cylinders were poured in two lifts and each lift vibrated with the high-frequency internal vibrator. In order to measure the internal temperature of the concrete, a 1-inch diameter pipe, extending one-half the depth of the cylinder (6 inches), was cast in one cylinder of each pour. When the concrete attained the initial set, the pipe was removed. All concrete was placed within 15 minutes of being discharged from the mixer.

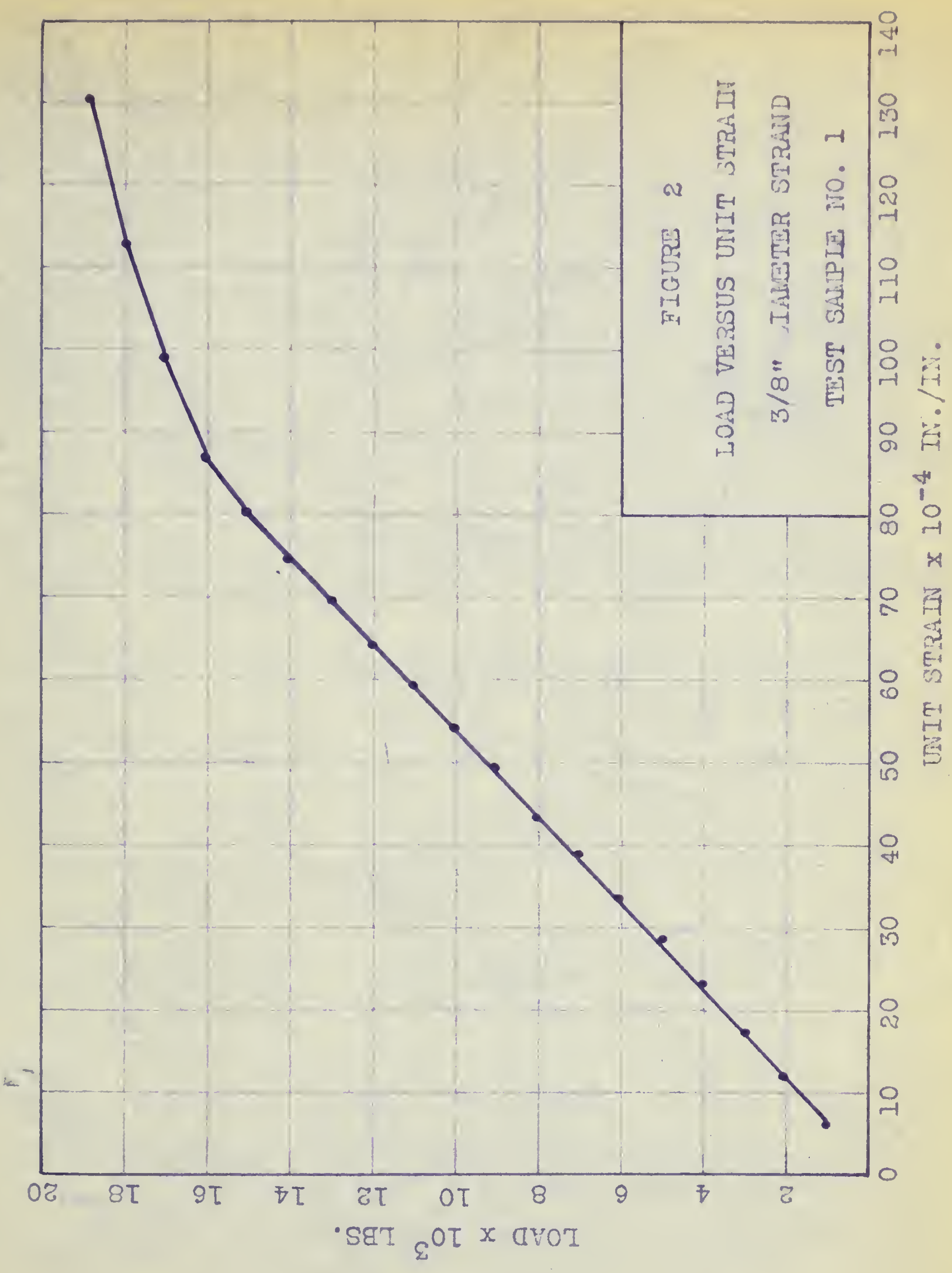

FIGURE 2
LOAD VERSUS UNIT STRAIN
3/8" DIAMETER STRAND
TEST SAMPLE NO. 1

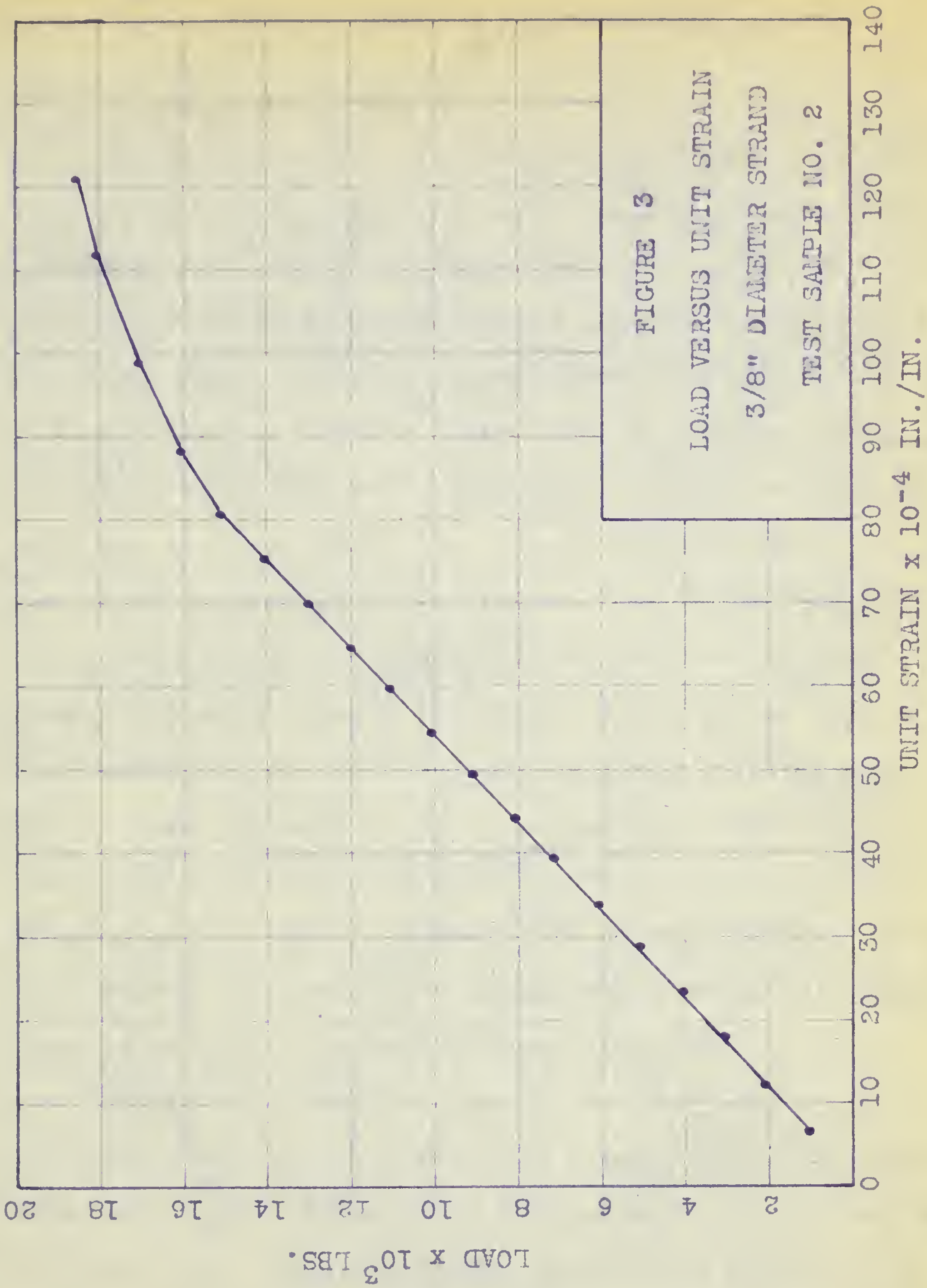

FIGURE 3

LOAD VERSUS UNIT STRAIN

3/8" DIAMETER STRAND

TEST SAMPLE NO. 2

CHAPTER 5: APPARATUS

5-1 Prestressing Frames

The special frame designed for the tests is shown in Figures 4A and 4. The frame was required to stress the strand before the concrete specimen was poured, and to provide restraint for one end of the prism when the strand was released. Basically, the frame comprises two rods and three plates. The two outside plates act as the abutments for the stressing operation while the inside plate restrains the specimen when one end of the strand is released. The rods are 1-3/4 inch diameter and 66 in. long. They are threaded for 24 in. on one end and 12 in. on the other. Each plate measures 6in. x 16in. x 1 in. with two 1 in. x 1 in. x 8 in. bars welded to one side of each plate as reinforcement. Twelve nuts are used to keep the plates in the desired positions. The three plates have 1-13/16in. holes drilled on 12in. centres and a 7/16in. hole drilled at the centre. The rods pass through the outside holes of the plates. The plates are kept in place by two nuts, one on each side.

5-2 Forms

The sides and bottom of the form were made of 3/4in. fir plywood (Figures 5A and 5). For convenience of handling, the sides were attached to the bottom with hinges. One end was formed by a 6in. x 16in. x 1 in. plate of the frame. The forms were oiled lightly with used SAE30 crankcase oil before casting the specimens.

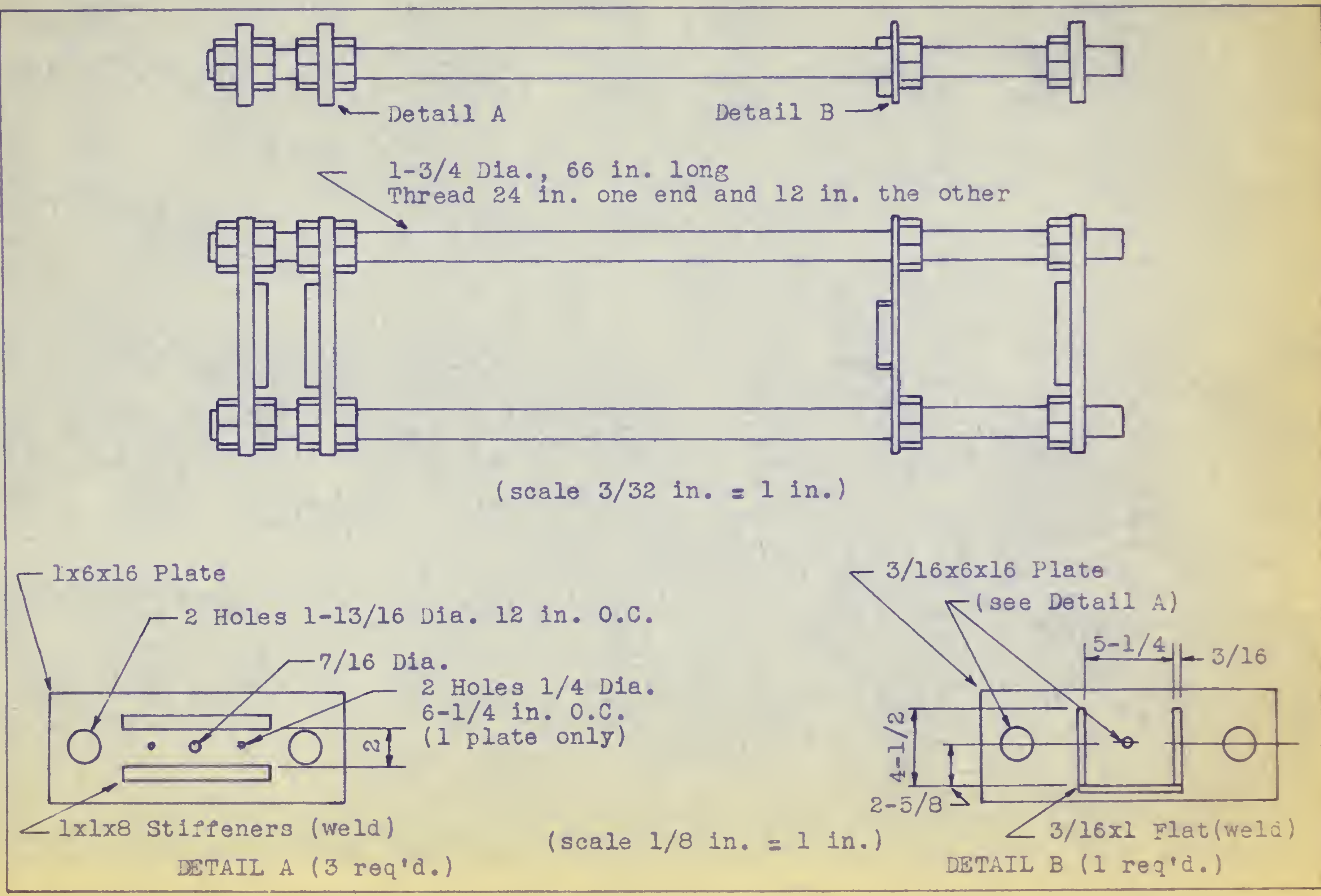

FIGURE 4A TESTING FRAME

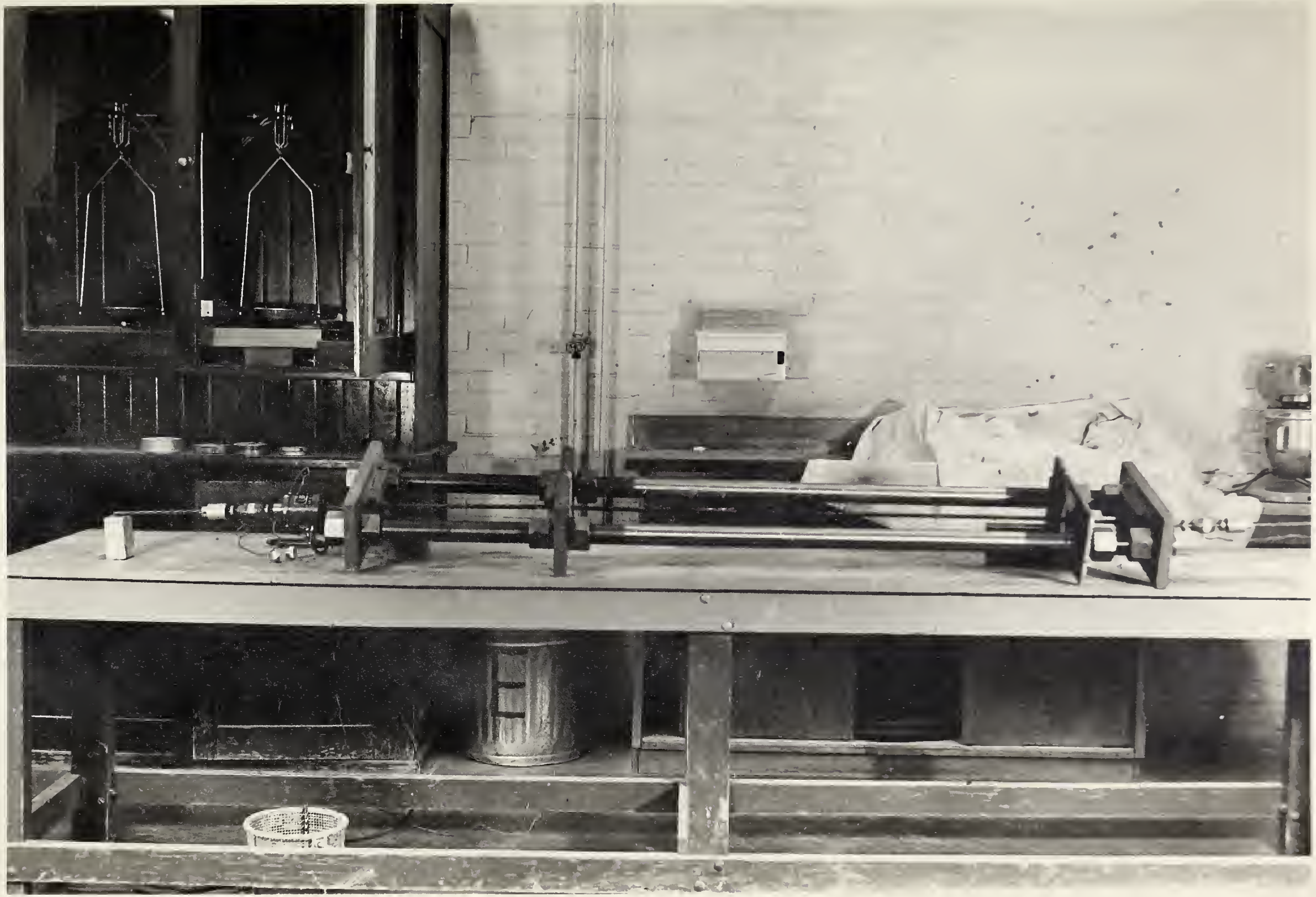

FIGURE 4 - TESTING FRAME WITH STRAND THREADED THROUGH PLATES READY FOR PRESTRESSING

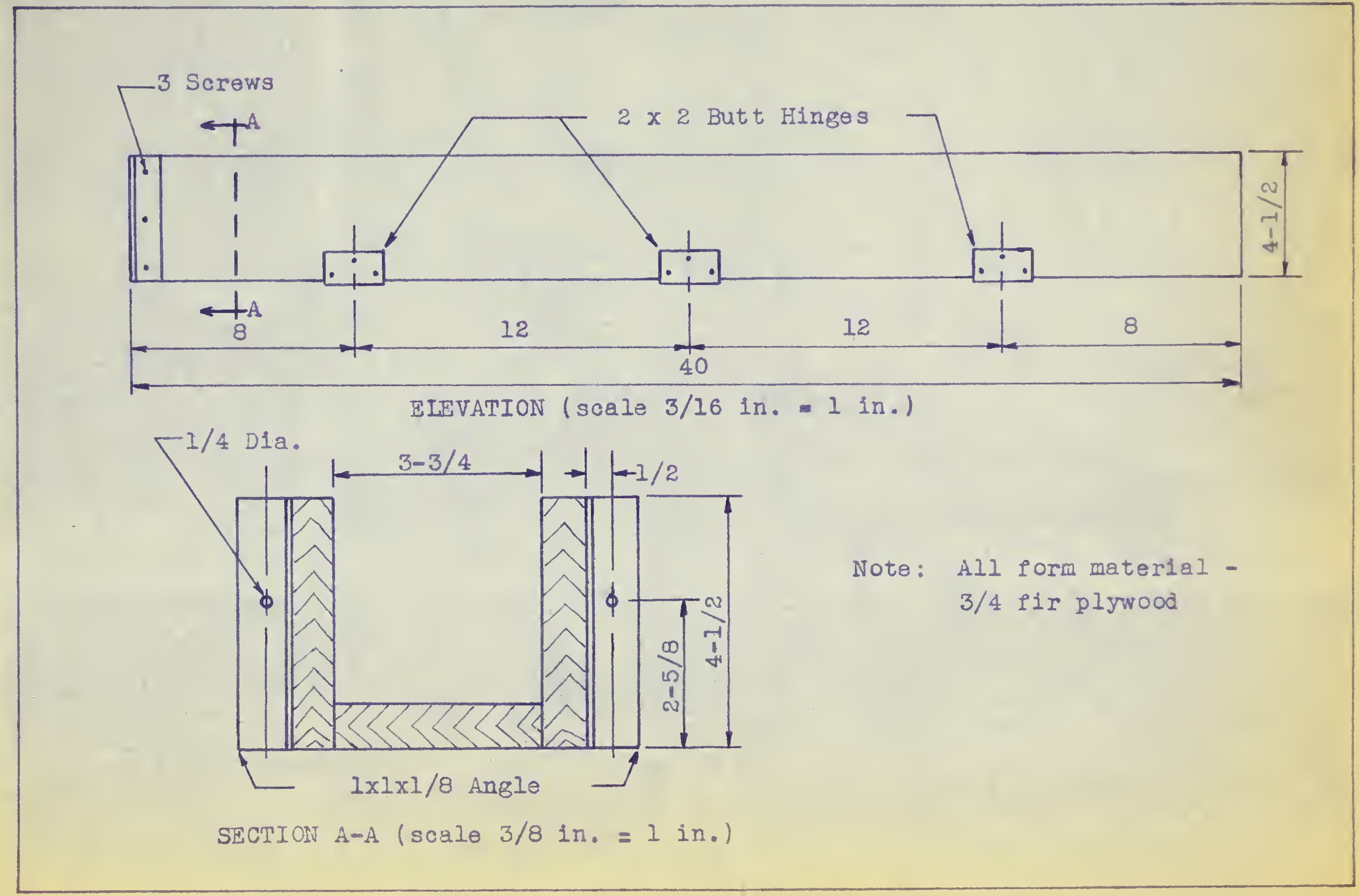

FIGURE 5A FORM FOR CONCRETE SPECIMEN

FIGURE 5 - STRESSING FRAME WITH PLYWOOD FORM IN POSITION

CHAPTER 6: INSTRUMENTATION

6-1 Load Measurement

Two dynamometers made from aluminum tubing; 2 inches long, 0.820 inches outside diameter and 0.400 inches inside diameter, were used on each strand to measure the load (Figure 4). These dynamometers were instrumented with four SR-4 strain gages oriented longitudinally on the outside surface and spaced 90 degrees apart. The four SR-4 strain gages were connected in series to indicate the average strain of the dynamometer.

The dynamometers were calibrated by placing them on a strand with a "Kyowa L.C. - 5/3" load cell, with a capacity of five tons, which had been previously calibrated in a compression machine. This enabled calibration under load conditions identical with those in the actual tests. The dynamometers were loaded and unloaded until there was no significant difference between two successive calibration readings. The dynamometers had a calibration factor of approximately 5 lbs. per dial division on the strain indicator which could be read consistently to about one dial division. The load cells had a calibration factor of about 10 lbs. per dial division, on the strain indicator, which could be read consistently to about one-half a dial division. The movement of the centre plate of the frame was measured with a dial gage measuring to an accuracy of 0.0001 inch.

6-2 Temperature and Relative Humidity Measurements

The temperature and relative humidity of the curing room were recorded by an automatic recorder connected to a dry and a wet bulb thermometer. The temperature of the concrete was read from a thermometer submerged in water in the 1-inch diameter well cast in the centre of one cylinder of each pour.

6-3 Longitudinal Strain Measurements

Strain was measured with a Demec strain gage locating onto 8-inch gage lengths formed by 0.04 inch diameter holes drilled in pairs of 1/4 inch diameter, 1/16 inch thick, stainless steel discs fixed to the surface of the member. To form the gage lengths the stainless steel discs were placed in an aluminum bar, 1/8in. thick, 3/4in. wide and 39½in. long; recessed 1/32in. at 2-inch centres to receive the discs. A specimen with the discs fastened to the surface is shown in Figure 1.

6-4 Stress-Strain Measurements on 6in. x 12in. Standard Concrete Cylinders

Compression tests on the concrete cylinders were run in a compression testing machine with an extensometer mounted on the cylinder (Figure 6). Strains were read on a 0.0001 inch "Mercer" dial mounted on the extensometer frame.

FIGURE 6 - A TEST CYLINDER WITH EXTENSOMETER ATTACHED - PLACED IN A BALDWIN COMPRESSION TESTING MACHINE

CHAPTER 7: PREPARATION OF SPECIMENS AND TESTING PROCEDURE

7-1 Prestressing

Prior to prestressing, the strand was threaded through the centre 7/16 inch diameter holes of the four plates of the frame (Figures 4A and 4). Two dynamometers were placed, one on each end of the strand, outside the end plates to measure the load in both the prestress and release operations. A strand grip was then fastened to each end of the strand to prevent it from pulling through when stressed.

The prestressing was produced by tightening the nuts bearing on the end plates. First one set of nuts was brought to the desired location, taking care that the end plate, when bearing on these nuts, was perpendicular to the rods. Then the prestressing was completed by tightening the nuts bearing on the other end plate, making sure that the tightening procedure was uniform for the two nuts. The strands were tensioned 24 hours before casting the specimen.

7-2 Casting of Specimens

The forms were oiled lightly with SAE30 used crankcase oil. Extreme care was taken to assure that no oil came into contact with the strand. The concrete was mixed in 3 cu.ft. batches and six 6in. x 12in. cylinders were cast with each group of three prestressed specimens. Immediately after casting, the top surfaces of the specimens and cylinders were struck off and trowelled. The top surfaces of the specimens were then covered with polyethylene film which was sealed tightly

around the specimens by taping to the sides of the forms. The tops of the cylinders were also sealed.

7-3 Preparation of Specimens

When cylinder compression tests indicated that the approximate desired concrete strength had been reached, the temperature in the curing room was lowered to approximately 70 degrees F. and the polyethylene covers were removed from prestressed specimens and cylinders. The plywood forms were then removed and a centre-line was marked on the top surface of the prism with a pencil. Two-inch centres were marked on the centre-line commencing one inch from the end of the specimen. A small amount of sealing wax was melted onto the concrete, at each mark, with a propane torch. The stainless steel discs were placed in the recesses of the aluminum bar. The discs were held in the recesses by a light film of grease placed over the recesses before the discs were inserted. The aluminum bar was placed upside-down on the centre-line of the specimen and positioned so that each disc rested on the sealing wax previously placed on the concrete. An electric soldering-iron was held to the point above each disc until the wax was melted and the disc was embedded in it. The same procedure was employed to fix gage discs to the bottom surface.

7-4 Release of Prestress

A Demec gage was used to obtain distances between the discs on the top and bottom of the specimens immediately prior to releasing the strand. The stressing force was

released at the rate of about 6,000 lbs. per minute by loosening the nuts supporting the end plate on the loaded side of the specimen. Demec gage readings were taken 12 hours and 36 hours after strand release.

7-5 Test Cylinder Compression Tests

Compressive strength tests were performed on the 6in. x 12in. cylinders in a compression testing machine at a rate of loading of approximately 3,000 p.s.i. per minute. All cylinders were tested to failure and the maximum load recorded.

7-6 Stress-Strain Readings on 6in. x 12in. Concrete Test Cylinders

Stress-strain relationships were obtained by testing cylinders, equipped with an extensometer, in a compression testing machine. Simultaneous readings were taken on the strain dial and the load indicator of the testing machine as the load was continuously applied. A loading rate of approximately 1,000 p.s.i. per minute was used in these tests.

CHAPTER 8: TEST RESULTS

8-1 Transfer Bond Strains

Tables 2, 3 and 4 and Figures 7, 8, 9 and 10 show the rate of increase in strain in the concrete as calculated from the strain readings on the surface of the specimens. The total strains in the 25-inch portion (the length measured from the end at which the strand was released) of each specimen are recorded in Table 5.

8-2 Stress in the 3/8in. Diameter Strand

The records of the stresses in the strands measured by the dynamometers are listed in Table 6.

8-3 Modulus of Elasticity of the Concrete

The variations in the modulus of elasticity of the concrete as obtained in cylinder tests are shown in Figures 12 and 13 and are listed in Tables 7, 8, 9, 10, 11, 12 and 13. The modulus of elasticity for various concrete compressive strengths are listed in Table 13A and modulus versus compressive strengths are shown in Figure 14.

8-4 Concrete Maturity and Compressive Strength

The maturity and compressive strength of all test cylinders is recorded in Table 14. A plot of maturity versus concrete compressive strength is shown in Figure 15.

8-5 Variation in Strain with Time

The increase in strain from 12 hours to 36 hours after release of the strand is shown in Tables 15, 16 and 17.

8-6 Average Bond Stresses

The average bond stresses in the transfer zone were calculated using the assumption that the bond is distributed uniformly throughout the transfer zone. The average bond stresses are listed in Table 18.

8-7 Corroboration of Transfer Bond Length

Table 19 lists the results of tests of the three groups of specimens with the bond broken by a plastic cover over the strand. The bonded lengths of strand (strand left in direct contact with concrete) are listed in each instance. The stress in the strands immediately before strand release, 12 hours after strand release, and 36 hours after strand release are also listed.

TABLE 2

STRAIN INCREASE AT TWO - INCH INTERVALS

Prism Mark	1-1	1-2	1-3	2-1	2-2	2-3
Concrete Strength p.s.i.	3065	3065	3065	5065	5065	5065
Distance From Released End	Strain x 10^{-4} Inches					
2"	0.9	2.9	3.3	4.6	4.9	4.6
4"	2.0	1.6	2.8	3.0	4.3	3.8
6"	3.1	1.7	2.4	1.8	2.3	3.0
8"	1.8	1.9	2.2	4.2	1.1	2.4
10"	2.7	2.0	3.3	5.5	1.5	2.1
12"	4.7	2.2	4.9	4.1	4.5	4.2
14"	5.1	2.9	4.7	2.7	5.8	6.3
16"	3.6	4.8	3.3	0.7	2.2	0.1
18"	3.6	5.3	1.2	0.1	0.9	0.1
20"	1.4	2.5	0.5	0.1	0.6	0.6
22"	0.3	0.7	0.9	0.2	0.9	0.1

TABLE 3

STRAIN INCREASE AT TWO-INCH INTERVALS

Prism Mark	3-1	3-2	3-3	4-1	4-2	4-3
Concrete Strength p.s.i.	4407	4407	4407	3097	3097	3097
Distance From Released End	Strain x 10^{-4} Inches					
2"	5.2	6.3	4.9	4.4	4.7	4.0
4"	4.4	3.5	3.8	3.8	3.6	3.5
6"	2.9	2.3	3.0	3.2	1.9	2.7
8"	1.4	2.4	2.4	2.9	1.8	2.5
10"	1.5	4.8	1.9	2.2	2.5	2.1
12"	2.5	4.8	2.7	3.4	4.0	3.2
14"	4.9	2.0	4.8	4.4	5.3	5.0
16"	4.2	0.7	3.6	2.4	3.4	4.2
18"	0.6	0.0	0.5	1.9	1.6	2.0
20"	0.4	0.4	0.5	0.4	0.4	0.5
22"	0.3	0.1	0.6	0.1	0.7	0.6

TABLE 4

STRAIN INCREASE AT TWO-INCH INTERVALS

Prism Mark	5-1	5-2	5-3
Concrete Strength p.s.i.	4412	4412	4412
Distance From Released End	Strain x 10^{-4} Inches		
2"	4.2	3.7	4.0
4"	2.3	2.3	2.8
6"	2.1	2.1	2.3
8"	2.1	2.0	2.3
10"	1.6	1.4	1.7
12"	2.6	3.2	2.0
14"	2.8	3.5	2.2
16"	3.7	4.1	3.9
18"	0.2	0.2	0.4
20"	0.9	0.2	0.2
22"	0.7	0.3	0.9

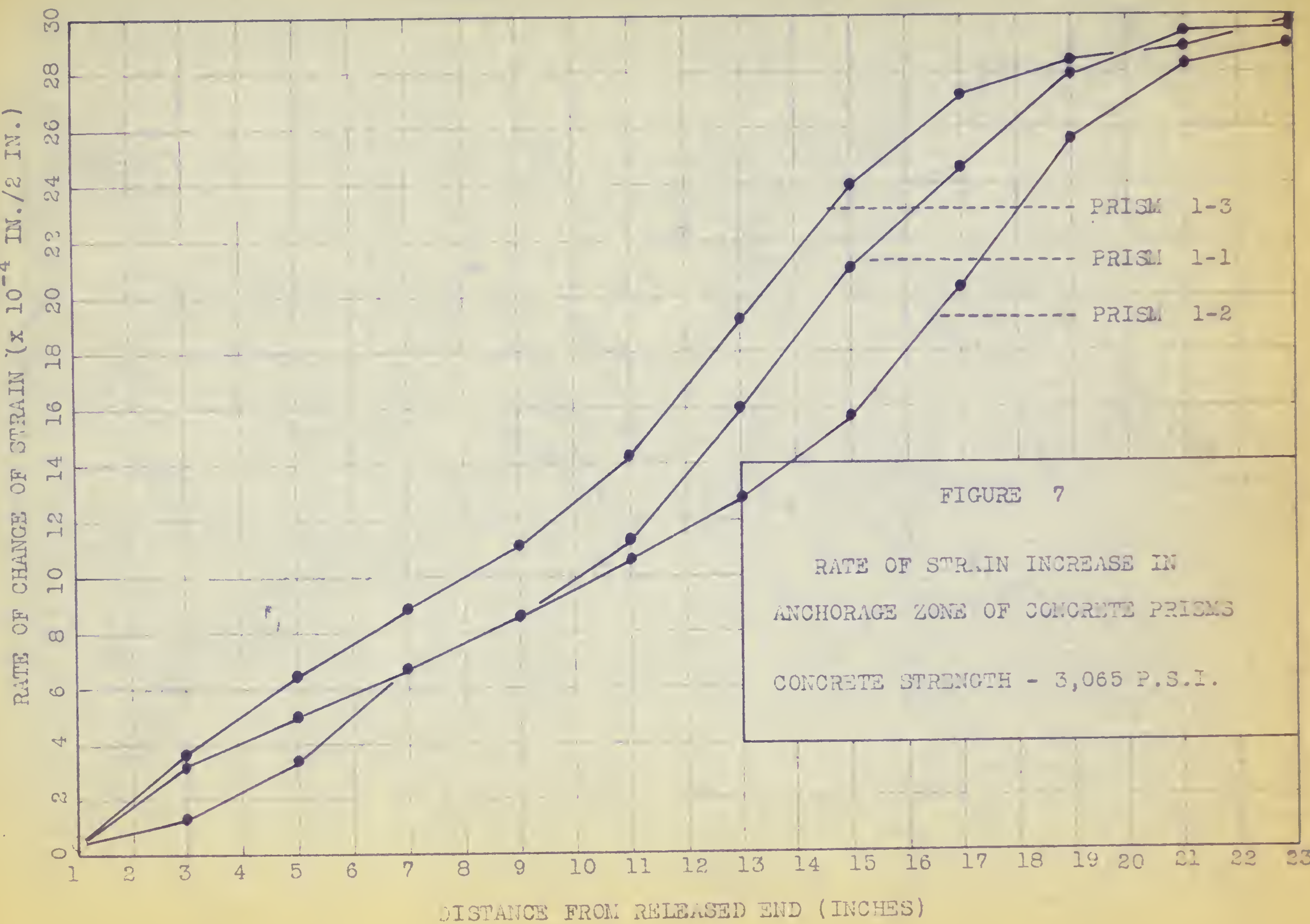

FIGURE 7

RATE OF STRAIN INCREASE IN ANCHORAGE ZONE OF CONCRETE PRISMS

CONCRETE STRENGTH - 3,065 P.S.I.

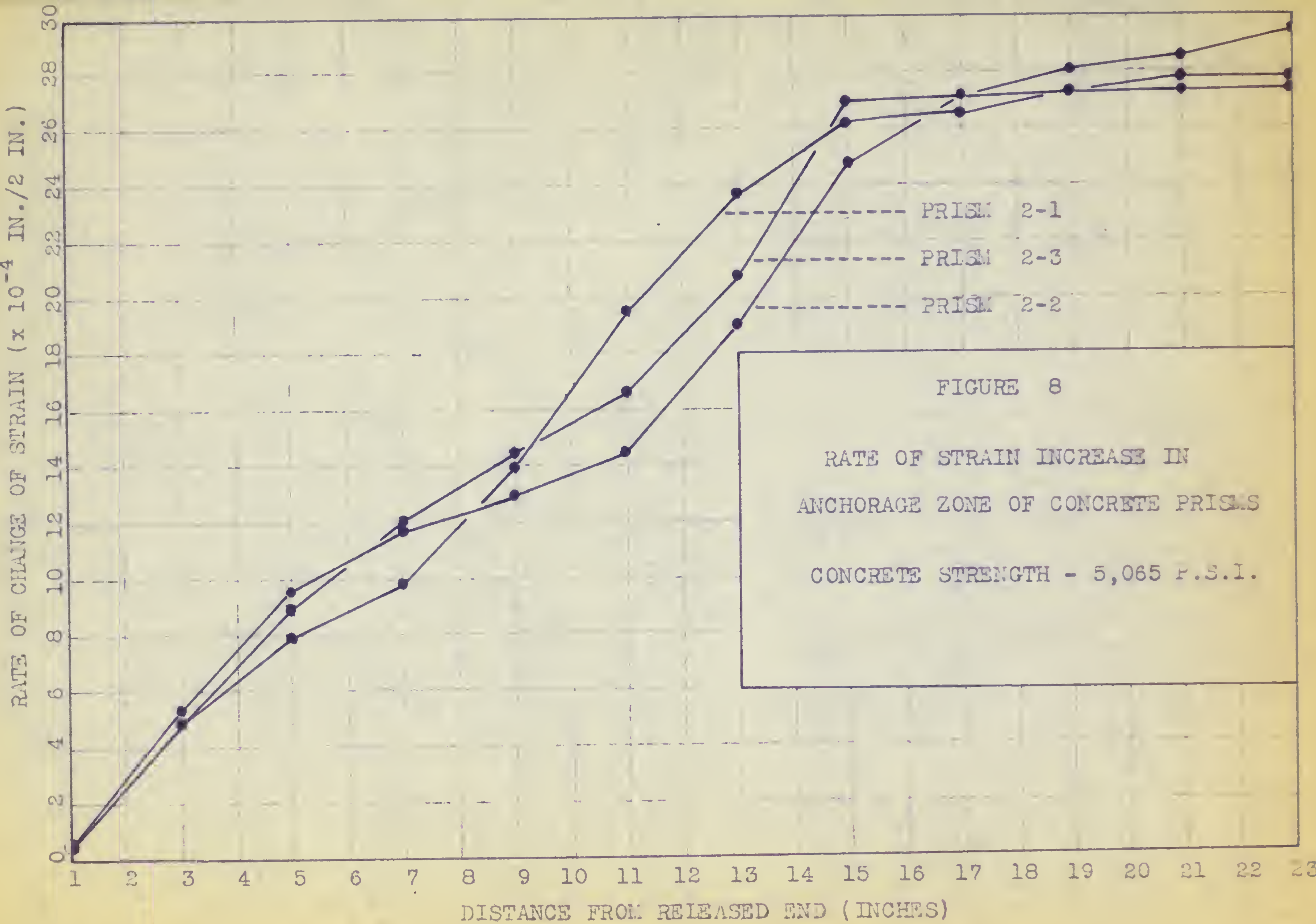

FIGURE 8

RATE OF STRAIN INCREASE IN ANCHORAGE ZONE OF CONCRETE PRISMS

CONCRETE STRENGTH - 5,065 P.S.I.

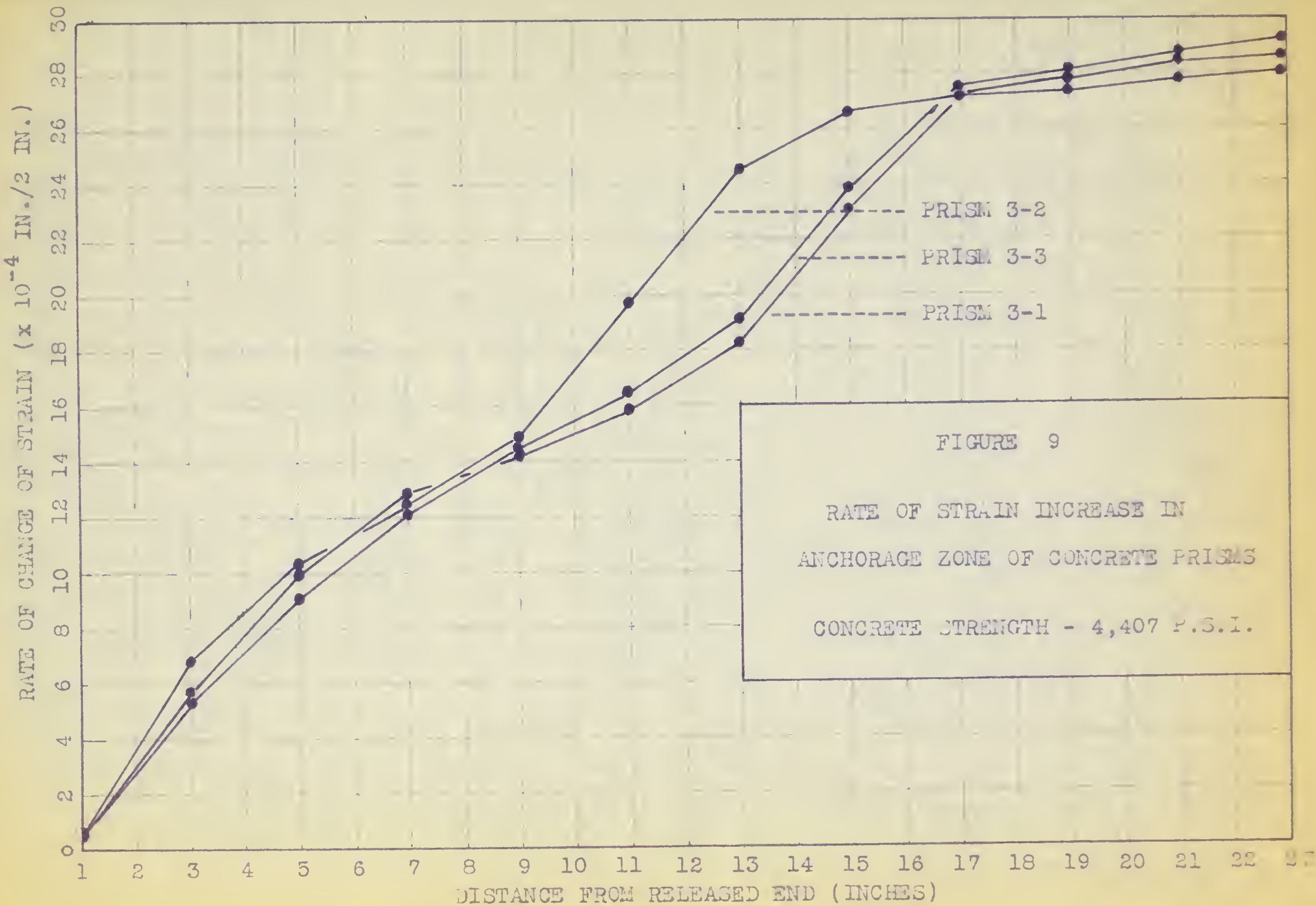

FIGURE 9

RATE OF STRAIN INCREASE IN ANCHORAGE ZONE OF CONCRETE PRISMS

CONCRETE STRENGTH - 4,407 P.S.I.

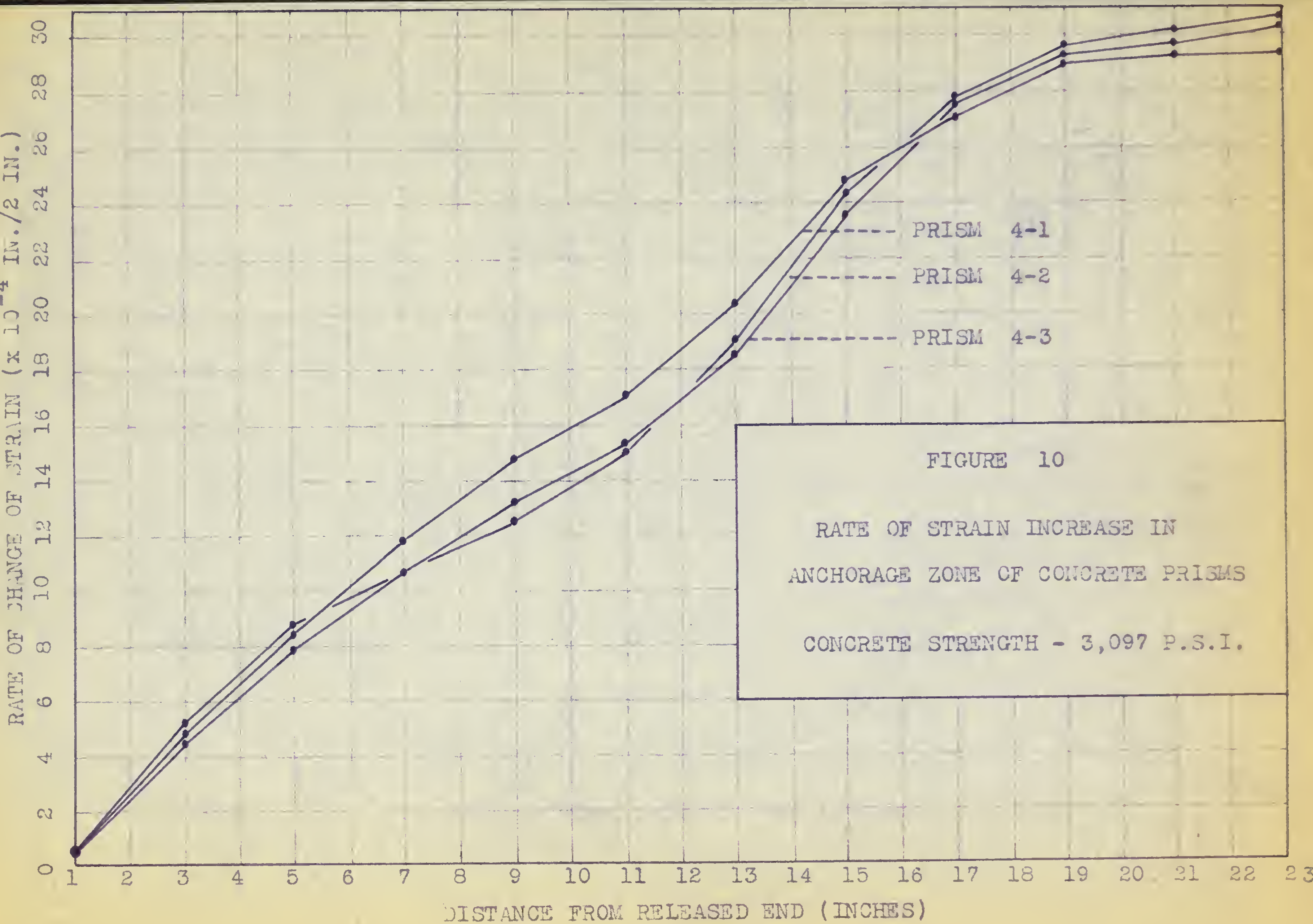

FIGURE 10

RATE OF STRAIN INCREASE IN ANCHORAGE ZONE OF CONCRETE PRISMS

CONCRETE STRENGTH - 3,097 P.S.I.

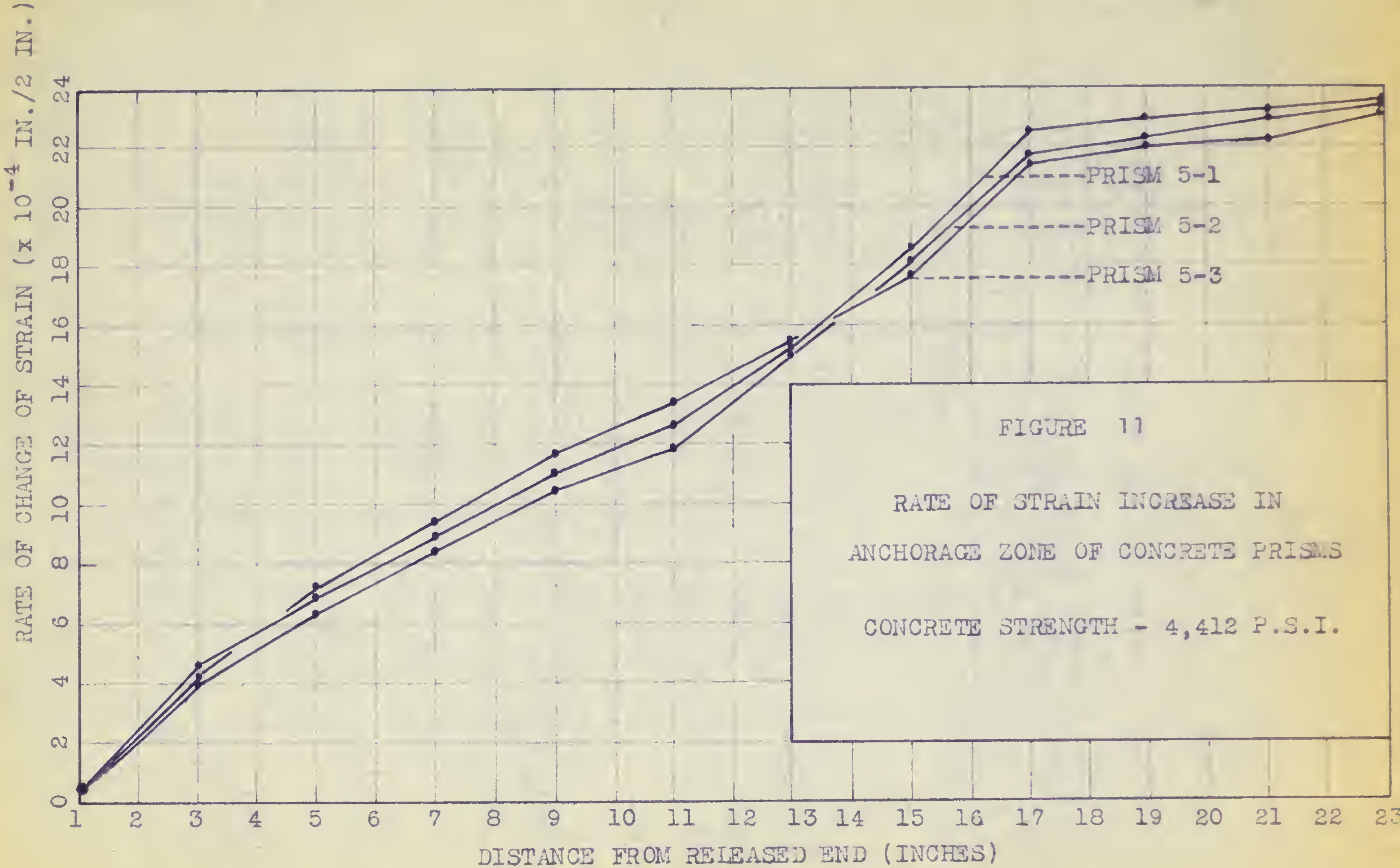

FIGURE 11

RATE OF STRAIN INCREASE IN ANCHORAGE ZONE OF CONCRETE PRISMS

CONCRETE STRENGTH - 4,412 P.S.I.

TABLE 5

TOTAL STRAIN 25 INCHES FROM RELEASED END OF BEAM

Prism Mark	Concrete Strength p.s.i.	Total Strain 12 hrs. (in. x 10^{-4})	Total Strain 36 hrs. (in. x 10^{-4})
1-1	3065	67.4	99.4
1-2	3065	68.0	91.8
1-3	3065	89.7	111.5
2-1	5065	82.8	111.7
2-2	5065	105.4	133.0
2-3	5065	100.9	126.9
3-1	4407	88.9	113.9
3-2	4407	107.0	131.7
3-3	4407	99.1	128.0
4-1	3097	107.0	122.0
4-2	3097	102.8	117.8
4-3	3097	105.6	122.4
5-1	4412	111.9	140.1
5-2	4412	92.6	115.8
5-3	4412	95.6	117.4

TABLE 6

STRESS IN STRANDS

Prism Mark	Concrete Strength p.s.i.	Strand Load Before Release lbs.	Strand Load 12 hrs. After Release lbs.	Strand Load 36 hrs. After Release lbs.	Load Loss At 12 hrs. lbs.	Load Loss 12-36 hrs. lbs.
1-1	3065	13761	12551	12328	1210	223
1-2	3065	13815	12565	12255	1250	310
1-3	3065	13743	12434	12223	1309	211
2-1	5065	13750	12690	12545	1060	145
2-2	5065	13623	12505	12356	1118	149
2-3	5065	13867	12738	12559	1129	179
3-1	4407	13813	12700	12490	1113	210
3-2	4407	13852	12711	12478	1141	233
3-3	4407	13924	12761	12539	1163	222
4-1	3097	13870	12671	12444	1199	227
4-2	3097	13875	12602	12360	1273	242
4-3	3097	13856	12560	12327	1296	233

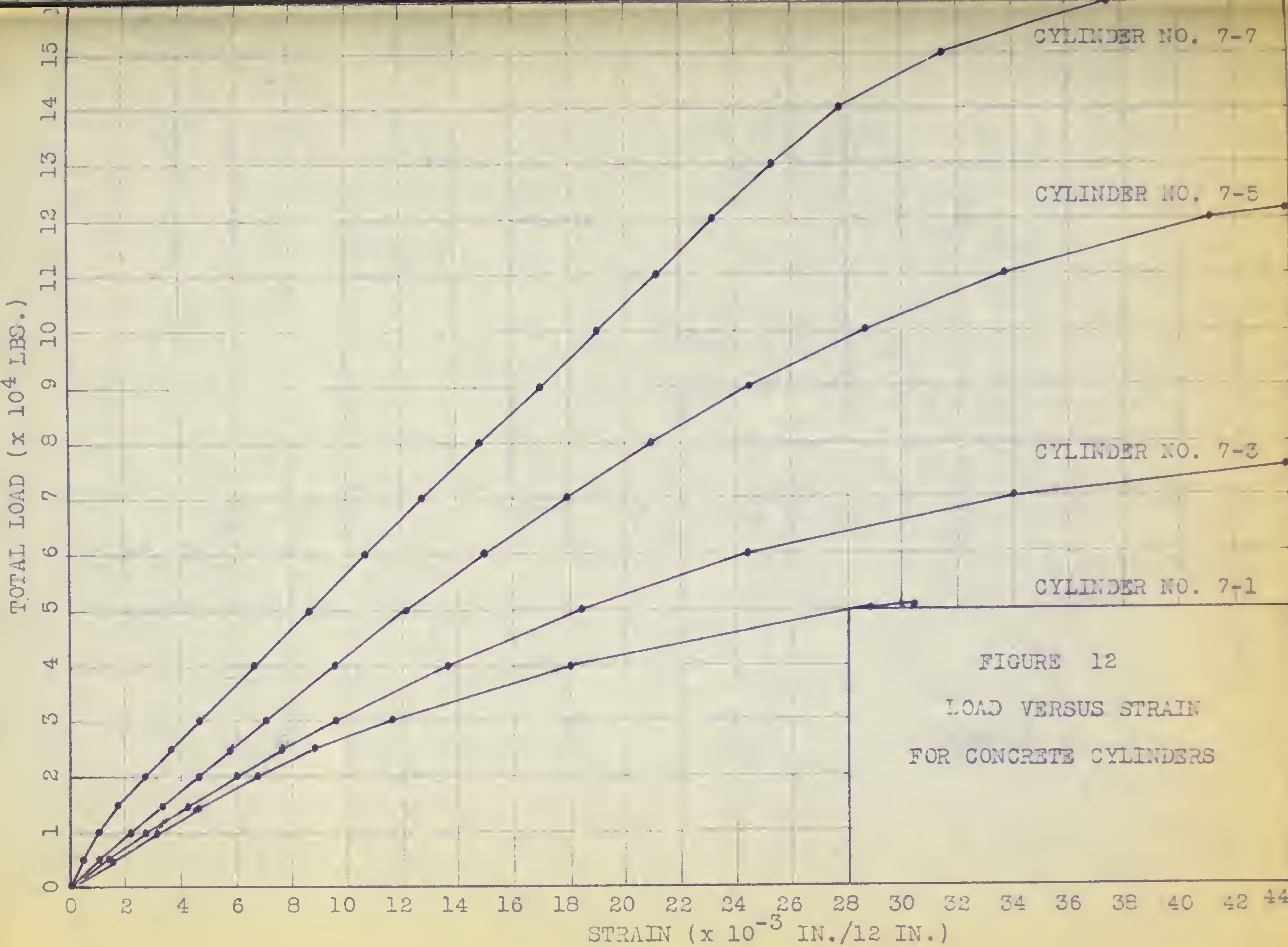

FIGURE 12
LOAD VERSUS STRAIN
FOR CONCRETE CYLINDERS

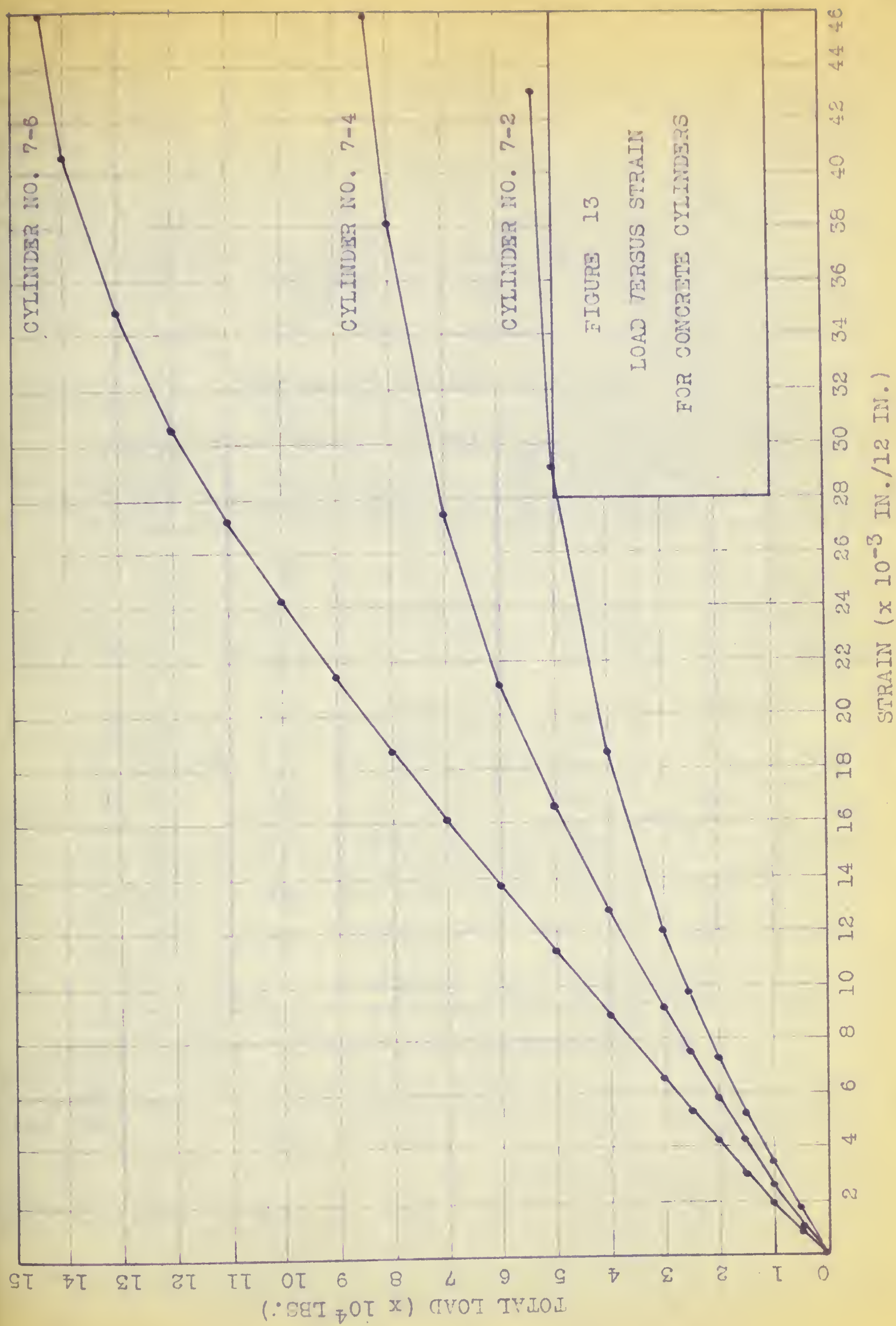

FIGURE 13
LOAD VERSUS STRAIN
FOR CONCRETE CYLINDERS

TABLE 7

STRESS-STRAIN DATA FOR CYLINDER NO. 7-1

Load (x 10^3 lbs.)	Gage Reading	Stress (p.s.i.)	Increment Strain (in.x10^{-4})	Total Strain (in.x10^{-4})	Rate of Loading
0	600	0	0	0	
5	615	176.9	15	15	
10	632	354.0	17	32	30,000
15	648	531.0	16	48	
20	666	708.0	18	66	lbs.
25	688	885.0	22	88	
30	716	1062.0	28	116	per
40	780	1416.0	64	180	
50	905	1770.0	125	305	min.
54		1910.0			

(reference data sheet no. 7)

TABLE 8

STRESS-STRAIN DATA FOR CYLINDER NO. 7-2

Load ($\times 10^3$ lbs.)	Gage Reading	Stress (p.s.i.)	Increment Strain ($in. \times 10^{-4}$)	Total Strain ($in. \times 10^{-4}$)	Rate of Loading
0	500	0	0	0	
5	516	176.9	16	16	
10	533	354.0	17	33	28,000
15	552	531.0	19	52	
20	573	708.0	21	73	lbs.
25	594	885.0	21	94	
30	618	1062.0	24	118	per
40	682	1416.0	64	182	
50	795	1770.0	113	295	min.
53.6	930	1894.0	135	430	

(reference data sheet no. 7)

TABLE 9

STRESS-STRAIN DATA FOR CYLINDER NO. 7-3

Load (x 10^3 lbs.)	Gage Reading	Stress (p.s.i.)	Increment Strain (in.x10^{-4})	Total Strain (in.x10^{-4})	Rate of Loading
0	1100	0	0	0	
5	1113	176.9	13	13	28,000
10	1128	354.0	15	28	
15	1144	531.0	16	44	
20	1160	708.0	16	60	lbs.
25	1178	885.0	18	78	
30	1196	1062.0	18	96	
40	1237	14.6.0	41	137	per
50	1287	1770.0	50	187	
60	1346	2120.0	59	246	
70	1441	2475.0	95	341	min.
77	1600	2720.0	159	500	
77.5	1665	2740.0	65	565	

(reference data sheet no. 7)

TABLE 10

STRESS-STRAIN FOR CYLINDER NO. 7-4

Load (x 10^3 lbs.)	Gage Reading	Stress (p.s.i.)	Increment Strain (in.x10^{-4})	Total Strain (in.x10^{-4})	Rate of Loading
0	200	0	0	0	
5	210	176.9	10	10	28,000
10	225	354.0	15	25	
15	241	531.0	16	41	
20	257	708.0	16	57	lbs.
25	273	885.0	16	73	
30	289	1062.0	16	89	
40	326	1416.0	37	126	per
50	365	1770.0	39	165	
60	410	2120.0	45	210	
70	475	2475.0	65	275	min.
80	572	2828.0	97	372	
84.5	680	2988.0	108	480	
84.7		2995.0			

(reference data sheet no. 7)

TABLE 11

STRESS-STRAIN DATA FOR CYLINDER NO. 7-5

Load ($x 10^3$ lbs.)	Gage Reading	Stress (p.s.i.)	Increment Strain ($in.x10^{-4}$)	Total Strain ($in.x10^{-4}$)	Rate of Loading
0	300	0	0	0	
5	310	176.9	10	10	
10	322	354.0	12	22	30,000
15	334	531.0	12	34	
20	346	708.0	12	46	
25	358	885.0	12	58	
30	371	1062.0	13	71	lbs.
40	396	1416.0	25	96	
50	424	1770.0	28	124	
60	449	2120.0	25	149	
70	479	2475.0	30	179	per
80	510	2828.0	31	210	
90	545	3180.0	35	245	
100	586	3538.0	41	286	
110	637	3885.0	51	337	min.
120	714	4240.0	77	414	
123.5	800	4365.0	86	500	

(reference data sheet no. 7)

TABLE 12

STRESS-STRAIN DATA FOR CYLINDER NO. 7-6

Load ($\times 10^3$ lbs.)	Gage Reading	Stress (p.s.i.)	Increment Strain (in.x10^{-4})	Total Strain (in.x10^{-4})	Rate of Loading
0	400	0	0	0	
5	408	176.9	8	8	
10	418	354.0	10	18	32,000
15	429	531.0	11	29	
20	441	708.0	12	41	
25	453	885.0	12	53	
30	464	1062.0	11	64	lbs.
40	488	1416.0	24	88	
50	512	1770.0	24	112	
60	536	2120.0	24	136	
70	561	2475.0	25	161	per
80	586	2828.0	25	186	
90	613	3180.0	27	213	
100	642	3538.0	29	242	
110	670	3885.0	28	270	min.
120	703	4240.0	33	303	
130	746	4590.0	43	346	
140	800	4950.0	54	400	
145.1	856	5130.0	56	456	

(reference data sheet no. 7)

TABLE 13

STRESS-STRAIN DATA FOR CYLINDER NO. 7-7

Load (x 10^3 lbs.)	Gage Reading	Stress (p.s.i.)	Increment Strain (in.x10^{-4})	Total Strain (in.x10^{-4})	Rate of Loading
0	500	0	0	0	
5	507	176.9	7	7	
10	515	354.0	8	15	32,000
15	524	531.0	9	24	
20	534	708.0	10	34	
25	544	885.0	10	44	
30	554	1062.0	10	54	lbs.
40	573	1416.0	19	73	
50	593	1770.0	20	93	
60	613	2120.0	20	113	
70	634	2475.0	21	134	per
80	654	2828.0	20	154	
90	675	3180.0	21	175	
100	697	3538.0	22	197	
110	718	3885.0	21	218	min.
120	739	4240.0	21	239	
130	761	4590.0	22	261	
140	785	4950.0	24	285	
150	823	5300.0	38	323	
160	887	5650.0	64	387	
190.5		6744.0			

(reference data sheet no. 7)

TABLE 13A

MODULI OF ELASTICITY

Cylinder No.	Concrete Strength (p.s.i.)	Secant Modulus (x 10^6 p.s.i.	Chord Modulus (x 10^6 p.s.i.
7-1	1910	1.098	1.010
7-2	1894	1.080	1.000
7-3	2740	1.328	1.248
7-4	2995	1.432	1.327
7-5	4365	1.795	1.731
7-6	5130	1.980	1.845
7-7	6710	2.360	2.233

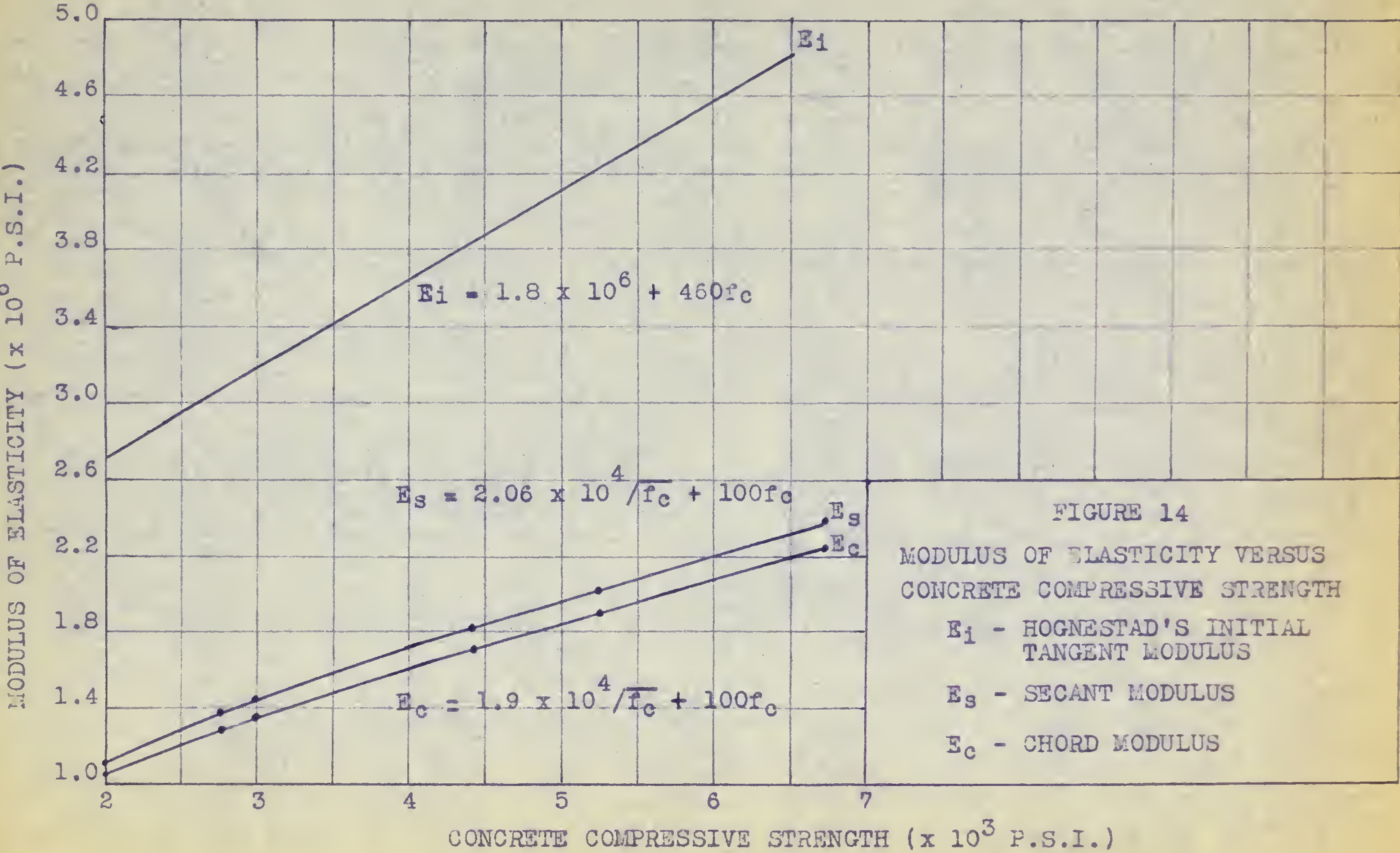

FIGURE 14

MODULUS OF ELASTICITY VERSUS CONCRETE COMPRESSIVE STRENGTH

E_i - HOGNESTAD'S INITIAL TANGENT MODULUS

E_s - SECANT MODULUS

E_c - CHORD MODULUS

TABLE 14

MATURITY OF CYLINDERS

Cylinder Mark	No. of Cylinders Tested	Av.Comp. Strength (p.s.i.)	Maturity (D.H.)	Slump (")	Humidity (%)
0-1 to 0-5	5	3620	2175	3	21
1-1	1	1900	1125	3	22
1-2	1	2280	1335	3	22
1-3 & 1-4	2	3065	1940	3	22
2-1	1	2475	1577	3	23
2-2	1	3700	2549	3	23
2-3	1	4780	4093	3	23
2-4 & 2-5	2	5065	4787	3	23
3-1	1	3350	1933	3	21
3-2 to 3-5	4	4407	2723	3	21
4-1	1	2380	1270	2.75	85
4-2 to 4-5	4	3097	1772	2.75	85
5-1	1	3520	1748	4.75	22
5-2 & 5-3	2	4412	2610	4.75	22
6-1 to 6-3	3	2197	1197	3	26
7-1 & 7-2	2	1902	1119	3	24
7-3	1	2740	1652	3	24
7-4	1	2995	1848	3	24
7-5	1	4370	3416	3	24
7-6	1	5130	6744	3	24
8-1 to 8-5	5	3029	1727	3	23
9-1	1	3660	2105	3	24
9-1 & 9-3	2	4440	3243	3	24
9-4 & 9-5	2	5120	4743	3	24
10-1 to 10-5	5	4248	2840	3	25

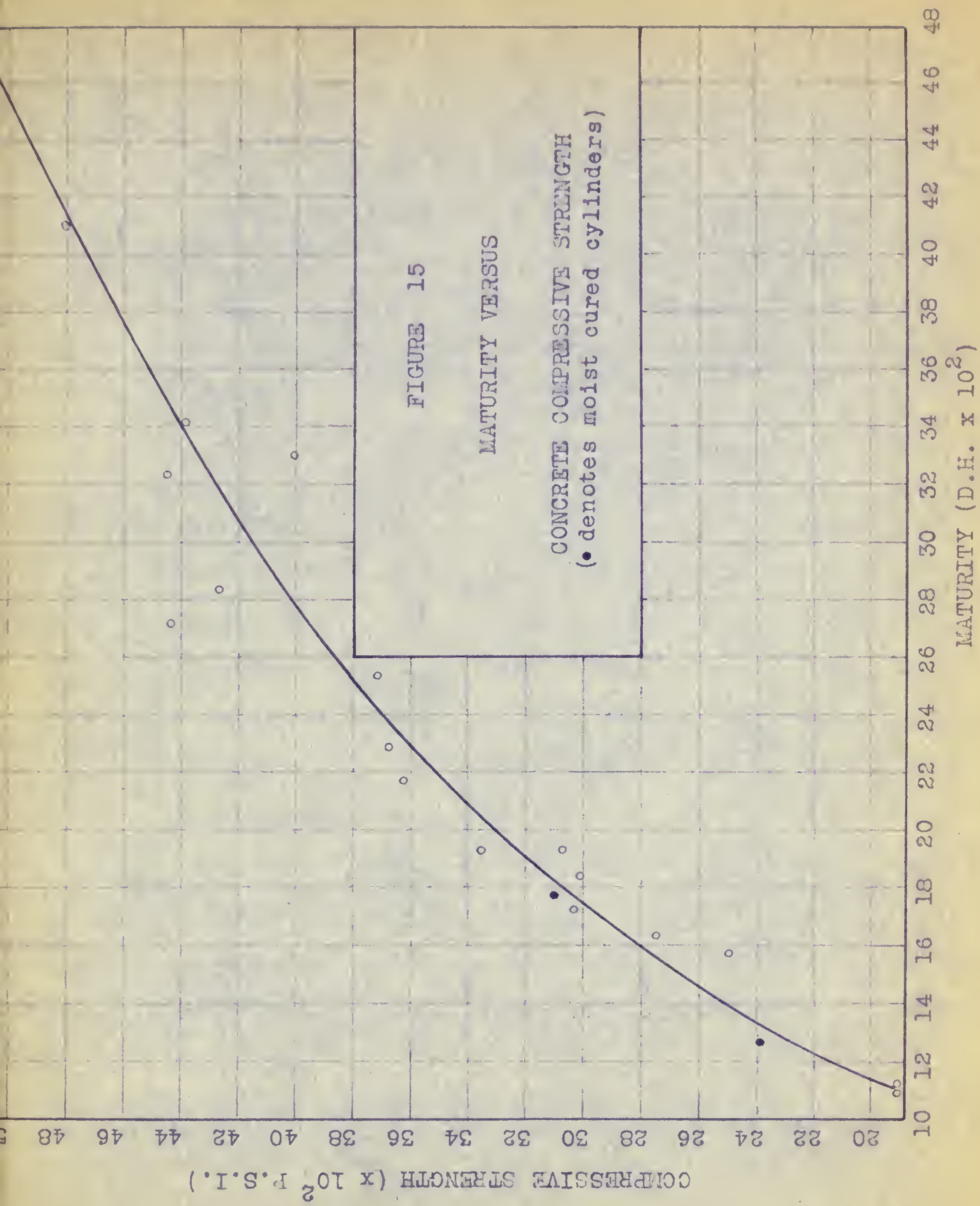

FIGURE 15

MATURITY VERSUS

CONCRETE COMPRESSIVE STRENGTH
(• denotes moist cured cylinders)

TABLE 15

STRAIN DIFFERENCE IN 12 AND 36 HOUR READINGS

Prism Mark	1-1	1-2	1-3	2-1	2-2	2-3
Concrete Strength (p.s.i.)	3065	3065	3065	5065	5065	5065
	Strain x 10^{-4} In.					
Difference	11.5	7.0	7.5	8.2	8.8	7.8
Between 8"	10.2	7.4	8.0	8.3	9.2	7.8
Demec Gage	9.2	5.4	7.2	9.0	9.1	7.7
Readings	10.5	8.8	6.3	9.1	9.7	8.0
At 2"	9.2	7.3	5.0	11.9	9.0	8.8
Intervals	10.5	8.7	6.8	9.2	9.4	8.0
Moving From	11.4	8.7	6.8	9.7	8.9	9.3
Released	12.0	9.6	8.4	8.4	9.4	9.8
End To	11.3	9.5	9.3	8.8	9.8	9.4
Loaded End	9.4	8.3	8.5	8.0	10.8	11.5
Of Prisms	12.3	10.4	7.7	8.2	11.1	9.5

TABLE 16

STRAIN DIFFERENCE IN 12 AND 36 HOUR READINGS

Prism Mark	3-1	3-2	3-3	4-1	4-2	4-3
Concrete Strength (p.s.i.)	4407	4407	4407	3097	3097	3097
	Strain x 10^{-4} In.					
Difference	7.0	7.4	8.6	4.9	5.0	5.6
Between 8"	7.7	8.0	8.1	4.9	4.8	5.4
Demec Gage	7.9	7.3	8.7	4.6	5.0	5.4
Readings	7.4	8.5	10.3	5.9	4.2	4.5
At 2"	8.3	8.1	10.4	4.4	3.8	4.1
Intervals	8.7	7.8	9.9	5.5	5.3	
Moving From	8.9	8.9	9.6	4.0	5.4	5.6
Released	10.2	8.6	10.5	3.3	6.0	6.0
End To	9.7	9.2	9.9	5.7	6.2	7.1
Loaded End	10.3	9.6	10.8	6.4	6.3	4.6
Of Prisms	10.7	11.8	11.0	4.7	5.6	6.9

TABLE 17

STRAIN DIFFERENCE IN 12 AND 36 HOUR READINGS

Prism Mark	5-1	5-2	5-3
Concrete Strength (p.s.i.)	4412	4412	4412
	Strain x 10^{-4} In.		
Difference	8.2	7.2	6.7
Between 8"	7.9	8.1	7.1
Demec Gage	9.2	7.7	7.0
Readings	9.4	7.2	7.1
At 2"	9.3	7.7	7.3
Intervals	9.8	7.4	6.8
Moving From	10.1	8.1	7.3
Released	10.2	8.3	7.5
End To	10.7	8.3	7.8
Loaded End	11.1	8.6	8.2
Of Prisms	11.2	8.7	8.4

TABLE 18

AVERAGE TRANSFER BOND STRESS

Prism Mark	Concrete Strength (p.s.i.)	Length of Transfer Zone (in.)	Strand Load (lbs.)	Average Bond Stress (lbs./lin.in.)
1-1	3065	21	12551	598
1-2	3065	21	12565	598
1-3	3065	19	12434	656
2-1	5065	15	12690	845
2-2	5065	17	12505	736
2-3	5065	15	12738	850
3-1	4407	17	12700	748
3-2	4407	15	12711	900
3-3	4407	17	12761	750
4-1	3097	19	12671	668
4-2	3097	19	12602	664
4-3	3097	19	12560	662
5-1	4412	17	12331	725
5-2	4412	17	12338	726
5-3	4412	17	12363	728

TABLE 19

TRANSFER BOND LENGTH

Prism Mark	Concrete Compressive Strength At Strand Release (p.s.i.)	Strand Length Allowed To Develop Bond (in.)	Load In Strands Immediately Before Strand Release (lbs.)	Load In Strands 12 Hrs. After Strand Release (lbs.)	Load In Strands 36 Hrs. After Strand Release (lbs.)
8-1	3030	14.25	13850	4530	4140
8-2	3030	19.00	13821	6495	6455
8-3	3030	23.75	13872	12645	12442
9-1	5120	11.25	13746	3654	3227
9-2	5120	15.00	13684	4028	3863
9-3	5120	18.75	13798	12755	12593
10-1	4248	12.75	13786	3566	3178
10-2	4248	17.00	13818	4262	4016
10-3	4248	21.25	13872	12769	12583

CHAPTER 9 : DISCUSSION OF TEST RESULTS

9 - 1 Concrete Strain Measurements

It would seem reasonable to assume that the rate of increase of the longitudinal strain on the surface of the concrete prism is directly proportional to the rate of bond transfer from the strand to the concrete over the same element of length. Figures 7 to 11 may therefore be interpreted as graphs of the rate of bond transfer. Figures 7 to 11 which are plots of rate of bond transfer show similar shaped curves for the three specimens in each group. The graphs indicate a similar rate of stress increase in the strands for a particular concrete compressive strength at strand release. Deviations in the strains at similar concrete strengths could be attributed to human error, differences in the surface condition of the strands, and/or variations in the consistency of the concrete.

There was a small increase in the bond transfer length with a reduction in concrete compressive strength at strand release. The transfer lengths for 3,000 p.s.i. and 5,000 p.s.i. concrete were 19 inches and 15 inches respectively. These results agree with the consensus that the compressive strength of the concrete has little effect on the bond strength when compared with other variables such as the condition of the surface of the strand, the amount of compaction of the concrete around the strand, the method of strand release, the depth of concrete under the strand and

the slump of the concrete.

The total strains in the 25-inch portion of each specimen do not show any trend for the specimens tested. Some of the properties that contribute to the magnitude of the total strain are the modulus of elasticity of the concrete, shrinkage of the concrete, and the magnitude of the stress in the strand. The total strains in the three specimens in which the strands were released at a concrete compressive strength of 3,065 p.s.i. are 99.4×10^{-4} inches, 91.8×10^{-4} inches and 111.5×10^{-4} inches. The total strains in the three specimens in which the strands were released at 5,065 p.s.i. are 111.7×10^{-4} inches, 133.0×10^{-4} inches and 126.9×10^{-4} in. The following factors could have contributed to the variations in the total strains: (1) The first disc was located one inch from the released end of the specimen; therefore the strain in the first inch was not included. (2) There was reason to doubt that drying had progressed the same amount in each specimen. The polyethylene covers were not airtight and moisture evaporated from the specimens at rates proportional to the circulation of air over the concrete surface. This could produce a variation in the strain because part of the total shrinkage is inversely proportional to the moisture in the concrete.

9-2 <u>Stress in the Strand</u>

Table 6 lists the stresses in the strands immediately before strand release, 12 hours after release, and 36 hours after release. There was a variation in the reduction in

stresses for the three specimens tested in each group. The largest variation was 7.6%. It was difficult to account for the stress reductions in the strand because (1) the relation between the strains on the surface of the concrete and the strains in the concrete adjacent to the strand were not known and (2) the exact loss of stress in the strands due to relaxation was not known.

9-3 Modulus of Elasticity of the Concrete

Stress versus strain curves as derived from tests on standard 6in. x 12in. concrete test cylinders are shown in Figures 12 and 13. The moduli of elasticity established from these curves are lower than other published values available. The consensus of other investigators is that the modulus varies inversely as the concrete design strength. Other factors that could contribute to the low values are: the smaller moisture content of the cylinders cured in air as opposed to those cured in steam; the relatively short curing cycle of the concrete; and the properties of the aggregates.

The modulus of elasticity is plotted in Figure 14 for various concrete compressive strengths. An equation for the chord modulus of elasticity derived from this data is:

$$E_c = 1.90 \times 10^4 \sqrt{f_c} + 100 f_c$$

An equation for the secant modulus of elasticity derived from this data is:

$$E_s = 2.06 \times 10^4 \sqrt{f_c} + 100 f_c$$

The two equations for the moduli of elasticity are plotted

in Figure 14. For comparison, Hognestad's initial tangent modulus calculated from equation $E_i = 1.8 \times 10^6 + 460\, f_c$ is also shown.

Part of the discrepancy between the secant and chord moduli was a result of a slight distortion of the curve at the beginning of the readings. There appeared to be some initial sticking of the recording gages. Investigation revealed that others had detected similar effects. Seabrook(10), Walker(11) and Blackman(12) reported initial curvature. The sticking was caused by slack in the assembly of the gages. The data could be corrected so that the initial tangent actually passes through the zero point.

9-4 Relation Between Maturity and Concrete Compressive Strength

The record of the maturity of all cylinders is recorded in Table 14 and the plot of maturity versus concrete compressive strength is shown in Figure 15. There is good agreement in all tests. The results for cylinders that were cured in the moist room also fall in the narrow band formed by the other points. Results indicate that if sufficient water is retained for hydration during warm-air curing, the concrete gains strength in relation to its maturity approximately in accordance with the same law as holds for normally cured concrete. No attempt was made to establish the optimum curing cycle, but all concrete was cured within the following limits: rise in concrete temperature never exceeded 20 degrees F. per hour; maximum temperature of concrete was

125 degrees F,; minimum temperature was 68 degrees F. and heating was delayed two hours after moulding.

9 - 5 Variation in Strain with Time

The increase in strain readings taken 12 hours after the strands were released and readings taken 36 hours after the strands were released are shown in Tables 15, 16 and 17. There was no indication of a change of strain distribution in the transfer zone during this interval. The strain increases oscillate about a mean and are similar for the entire length of the specimens. The only group of specimens that exhibited a distinct difference were the specimens cured at the higher relative humidity. Because of the high moisture content of the specimens, total shrinkage was less.

9 - 6 Average Bond Stress

It was assumed that the bond was distributed uniformly throughout the transfer zone, for calculations of average bond stress. The average bond stresses are tabulated in Table 18. The trend was toward higher bond strength with higher compressive strength of the concrete, but the increase was small, i.e., the average bond stress was 524 p.s.i. for concrete with a compressive strength of 3,065 p.s.i., and the average bond stress was 689 p.s.i. for concrete with a compressive strength of 5,065 p.s.i. Keuning[5] found the average bond stress for 1/4-inch diameter strand to vary from 590 p.s.i. to 720 p.s.i. for concrete compressive strengths of 4,460 p.s.i. and 5,440 p.s.i. respectively.

9 -7 Transfer Bond Lengths

Table 19 lists the results of three sets of specimens tested to confirm the bond transfer lengths for the three concrete strengths used in the tests. Because the shape of the stress block in the transfer zone was not known, it was desired to confirm that the bond transfer was complete in the proximity of the point indicated by strain measurements on the concrete surface. The three specimens in which the bond was broken except for a length equal to 75% of the average required transfer bond length as indicated by the strain readings, all failed in general bond slip. This confirmed that the transfer bond length required in all instances was greater than 75% of the length as indicated by the surface strain readings. The three specimens in which the bond was broken except for a length equal to 100% of the required length as indicated by the surface strain readings, also failed in general bond slip. These results were anticipated since in the completely bonded specimens there would probably be a certain amount of bond developed in the remainder of the specimen length. The three specimens with the bond broken except for a length equal to $1\frac{1}{4}$ times the average required length as indicated by the surface strain readings, retained stresses in the strands similar to the stresses recorded in the strands in Table 6. The results located the ranges of the bond transfer length required for 3/8 in. diameter strand stressed to 14,000 lbs. as follows:

(1) for a concrete compressive strength of 3,030 p.s.i.

between 19in. and 24in., (2) for a concrete compressive strength of 4,248 p.s.i. between 17in. and 21in., and (3) for a concrete compressive strength of 5,120 p.s.i. between 15in. and 19in. The results substantiated the bond transfer lengths indicated by the strain readings on the surface of the specimens for the three concrete strengths used in the tests.

CHAPTER 10: RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

10-1 Future Investigations of Bond Transfer Length in Concrete Beams Prestressed with Strand

This present investigation indicated that concrete strength has little effect on bond stress developed in the anchorage zone, and therefore on the length of embedment required to develop the stress in the strand. Other investigations have revealed that beams prestressed with strand are susceptible to failure precipitated by tensile cracks through the weakest section of the concrete in the transfer zone. This would indicate that the criterion of failure is the lateral strain of the concrete, caused by the expansion of the strand, exceeding its limit. It is therefore suggested that in future investigations lateral strain should be measured over a range of concrete strengths at strand release to establish the relationship between lateral strain and concrete strength.

10-2 Future Investigations of Concrete Cured with Forced Warm Air.

A more extensive investigation of concrete heated by forced warm air could establish the optimum curing temperature and relationship between maturity and concrete strength for a wider variety of concrete mixes.

CHAPTER 11: CONCLUSIONS

11-1 Summary

Conclusions based on the results of this investigation are summarized as follows:

1. The length of the anchorage zone increases with a decrease in the concrete compressive strength at strand release.
2. The tests show that if the temperature gradient of the concrete does not exceed 20 degrees F. per hour, concrete sealed with polyethylene covers and heated with forced warm air gains strength in relation to its maturity approximately in accordance with the same law as holds for normally cured concrete.

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